Natural Survivorship estimates for the West Coast rock lobster *Jasus lalandii* obtained using a size-based modelling approach.

by

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Supervisor: Dr M.O. Bergh

To my parents, and to Patrick.

Table of Contents

Abstract

Natural survivorship for the South African west coast rock lobster resource, *Jasus lalandii*, is estimated at two locations, Robben Island and Hout Bay. A size-based modelling approach is used, in which the model is fitted to *pristine* catch size frequencies. The natural survivorship value for lobsters in the Robben Island region is estimated to be 0.94. The natural survivorship value for Hout Bay lobsters is estimated to be 0.87. The natural survivorship estimates are found to be very sensitive to rock lobster growth rate. The Robben Island estimate decreases from 0.968 for a decrease of 40% in the growth rate, to 0.917 for a increase of 40% in the growth rate. These estimates are compared with those made for lobsters in more northern areas. The implications of these natural survivorship estimates are discussed. A simple, direct method is used to estimate natural survivorship for Robben Island and Hout Bay, and the results are compared to those obtained with the model.

Assuming that the s=0.94 estimate obtained for Robben Island is representative of Dassen Island, the value of PROP (where $PROP = 1 - e^{-F_i}$) of 0.35 for Dassen Island for the last eight years of is estimated. Sustainable yields versus stock biomasses are calculated in all three regions. The MSY (maximum sustainable yield) biomass levels are low, varying from 0.16K (Hout Bay), 0.18K (Dassen Island) to 0.20K (Robben Island) (K=the unexploited carrying capacity of 89mm and larger lobsters). The $PROP_{MSY}$ values vary from 0.11 for Robben Island, 0.13 for Dassen Island and 0.41 for Hout Bay.

On the basis of these results, 50 year projections of catch and biomass are made for Robben Island and Hout Bay. These projections suggest that a large pool of unexploited accumulated stock exists at pristine levels, that this sustains large catch levels for an initial period, and thereafter the stock

is rapidly reduced to a level at which only relatively small sustainable catches can be maintained.

Introduction

The west coast rock lobster, *Jasus lalandii*, occurs in the waters off South Africa and Namibia, and is exploited commercially in both these territories (Heydorn 1965). The exploitation of the west coast rock lobster is one of the oldest and most important aspects of the South African fishing industry (Heydorn, Newman and Rossouw 1965). The rock lobster resource is presently one of the most valuable in the South African fishing industry. The fishing technique used for catching lobsters involves the use of baited nets and traps.

Critical information for the quantitative management of the resource is the relationship between surplus production and standing stock. Natural mortality is a crucial factor in the determination of the sustainable yield – standing stock relationship.

This study is concerned with estimating natural survivorships for *Jasus lalandii* in two regions: Robben Island and Hout Bay (Figure 1). The natural survivorship (s) of a population is the proportion of individuals that survive natural mortality (M) from one year to the next. Natural survivorship and natural mortality are related by $s = e^{-M}$. The current PROP value (where $PROP = 1 - e^{-Fi}$) for the important commercial fishing area of Dassen Island is then estimated using the natural survivorship estimate for Robben Island (a nearby region).

The natural survivorship estimates are subjected to a number of sensitivity tests, in which the various parameters associated with the growth rates of the lobsters are altered, and different portions of the pristine size frequency are downweighted or removed from the estimation procedure.

Sustainable yield versus biomass relationships are calculated for all three areas (Robben Island, Hout Bay, and Dassen Island), in order to determine the relationship between the maximum sustainable yield (MSY), the biomass level at which MSY occurs (B_{MSY}), and the PROP value that is required to reach MSY, ($PROP_{MSY}$). Using these estimates of natural survivorship, 50 year catch and biomass projections are made for Robben Island and Hout Bay. In both cases the population is assumed to be at a pristine state at year one. A number of different fishing mortality scenarios are considered to determine how long the accumulated pristine stock can be harvested at high levels, before reducing the population to levels at which only relatively small sustainable catches can be maintained. Projections are also made for Dassen Island – but in this case year one is assumed to be the present heavily exploited state of the resource, and projections of 50 years into the future are made using catch scenarios that assume an MSY management strategy.

Natural survivorship and mortality estimates have been made for *Jasus lalandii* by a number of researchers, using a variety of different methods. Newman (1973) estimated M from tagging data collected in 1969–1971 from Dassen Island and the Cape Peninsula at between 0.04 to 0.12 yrs^{-1}, that is $0.89 \leq s \leq 0.96$.

Pollock (1978) estimated M for male *Jasus lalandii* at Robben Island using two methods. The first method used Beverton and Holts' equation. An instantaneous natural mortality rate of 0.44 was estimated using this method. In the second method, Pollock made use of length frequency distribution information of males and females and growth rate measurements, all for the Robben Island region *ca* 1973. The instantaneous natural mortality rate estimated from this method was 0.46. Pollock also calculated size-specific mortality rates and found these to vary from M=0.10 (for size-class 8cm) to M=0.70 (for size-class 11.5cm). Pollock suggested however that the rate of M

of 0.1 to 0.2 recorded for the 7.5 to 9.4cm size-classes was probably a more realistic rate of M than the averaged 0.44 and 0.46 estimated for all size-classes combined. Pollock later uses an M of 0.1 in his lobster population dynamic studies (Pollock 1987).

Natural survivorship estimates for *Jasus lalandii* are reported by Barkai and Bergh (1990) using a size-based population model for lobster populations in Zone A (a lobster fishing area just south of the Orange river). Using pristine size frequencies from the Tristan group of islands, Vema Seamount, experimental catches in Luderitz, and a catch size frequency distribution from the Namaqualand region of the West coast, they estimated s to lie between 0.93 and 0.98 (68% confidence limits).

Natural mortality estimates for a number of other lobster species have been reported in the literature. Morgan (1977) estimated M at 0.23 for adult *Panulirus longipes cygnus* in Western Australia. Anthony and Cooper (1977) assumed M to be low in *Homarus americanus*, and used M values ranging from 0.05 to 0.2 in their studies.

The importance of natural survivorship

In order to explain why s is so important, I consider a simple constant recruitment model for a renewable resource under equilibrium conditions. In the population, let the annual recruitment = R. It follows therefore that
age 1 survivors = sR,
age 2 survivors = s^2R, and
age n survivors = s^nR.

We define the minimum harvestable age to be k, so that the number of an-

nual entrants into the population is $s^k R$.

At the beginning of the year, a proportion p is harvested, and so the number of pre-harvest individuals is equal to

$s^k R + s^{k+1}(1-p)R + s^{k+2}(1-p)^2 R + ...s^{k+n}(1-p)^n R$. For $n = \infty$, this reduces to a pre–harvest stock size by number

$$= \frac{s^k R}{(1 - s(1-p))}. \tag{1}$$

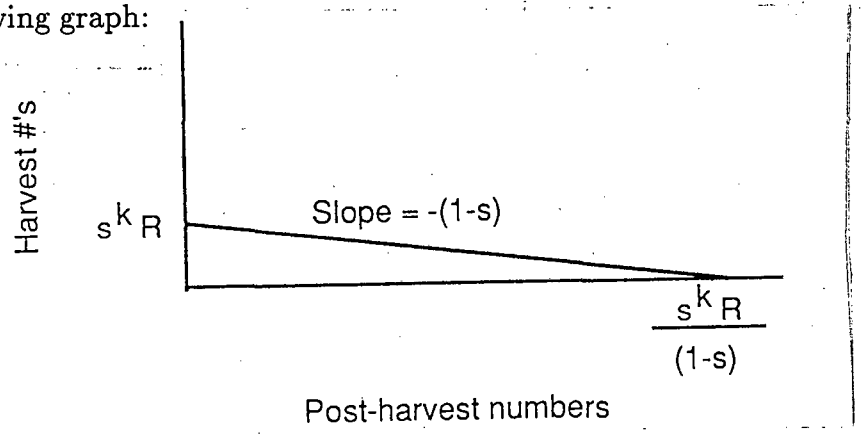
The harvest is p times this figure, that is,

$$HARVEST = \frac{p s^k R}{(1 - s(1-p))} \tag{2}$$

The number of individuals remaining after harvesting, the post–harvest population size, is equal to,

$$\frac{(1-p)s^k R}{(1 - s(1-p))} \tag{3}$$

If one plots the post-harvest numbers against the harvest numbers, one gets the following graph:



The plot of harvest versus post–harvest stock is not necessarily linear. A straight line however joining the extreme points as shown in the above figure captures the essential surplus production–standing stock characteristics.

The slope of the line is $-(1-s)$, that is, as s increases, surplus production becomes a much smaller fraction of the standing stock. Therefore natural survivorship is one of the most important parameters underlying the population dynamics of the west coast rock lobster resource. The model shows that a resource with a very high natural survivorship, will result in a very large unexploited accumulated stock. At the onset of harvesting this large accumulated biomass can give the false impression that large amounts of stock can be removed on a long term basis.

Harvesting should however be reduced to conform to the low sustainable yield potential of the resource once the *accumulated* stock has been removed.

A high s was estimated for the rock lobster resource along the Namaqualnd coastline (Barkai and Bergh 1990). As mentioned earlier, the high s for these lobsters leads to a very large accumulated unexploited stock. This accumulated stock apparently reached its final stage of depletion in the late 1960's, and since about 1970 the catches have become increasingly dependent on sustainable yield, which is only a small fraction of historic catches.

Other theories for low rock lobster catches in Namaqualand have been proposed. Pollock and Shannon (1987) have postulated that a progressive expansion of oxygen deficient shelf water may have forced the lobsters to occupy a much reduced habitat in shallower waters, where overcrowding has resulted in decreased growth rates and survival, therefore resulting in declines in production and yields.

In this study, environmental factors are not considered, and inherent parameters such as s and growth rates, controlling the dynamics of the population, are assumed to be the important factors to consider when examing the past catch histories of the resource and in determining sustainable yields.

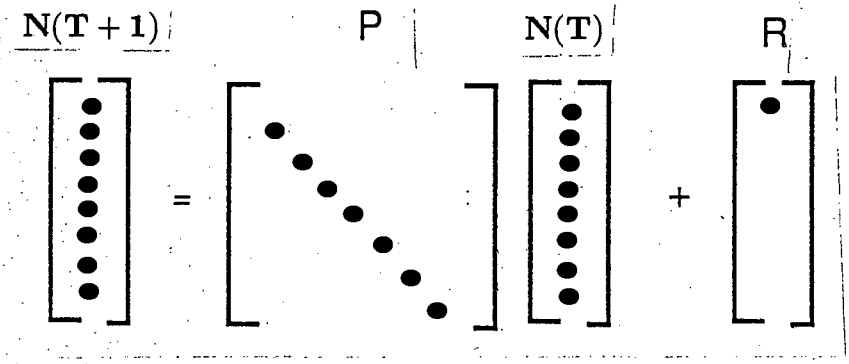
The problem of low sustainable yields following large harvests of accumulated stock over a number of decades, as seen for Zone A, could become a reality for the lobster industries in southern regions of the west coast. Available information showes that catches from all west coast management zones have been decreasing over the years (Pollock and Shannon 1986). Natural survivorships for these southern regions are required as critical input to determine whether a Zone A scenario might develop in the south.

Estimation of natural survivorship from population size frequency information

At present it is not possible to age rock lobsters reliably, although Lipofuscin techniques have been proposed. A large amount of size structure information is however available and a size-based population model can therefore be used to estimate s. Length data are simple and cheap to obtain, and large sample sizes are usually feasable. Fishing mortality and natural mortality are likely to be size-dependent rather than age-dependent, thus making the use of a size-based model particularly useful.

The standard age structure population model is that due to Lewis (1942), and later by Leslie (1945, 1948). This model assumes that births are proportional to adult numbers. The model which is comonly used is the modified Leslie matrix model incorporating constant recruitment, which can be de-

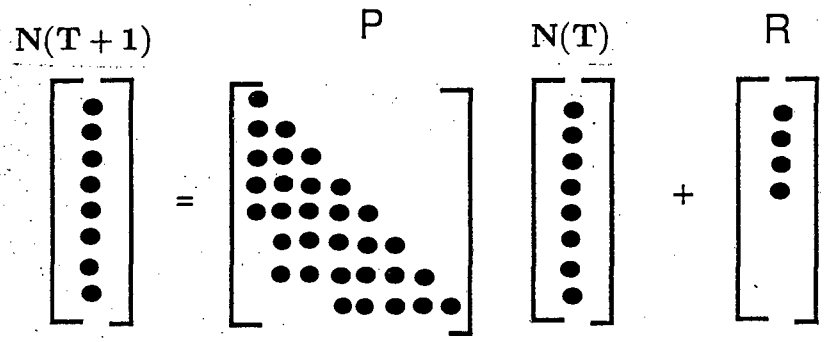
picted as: The modified constant recruitment Leslie matrix model



where the population at time T is represented by a population vector $\mathbf{N(T)}$. The entries of the population vector $\mathbf{N(T)}$, $N_i(T)$, represent the number of animals present between ages i and $i+1$. The population vector at T+1, $\mathbf{N(T+1)}$,is calculated by multiplying the vector $\mathbf{N(T)}$ by a population projection matrix $(\mathbf{P})$ which contains age specific survivorships, and by then adding on the constant recruitment $\mathbf{R}$ (recruitment is into the first size-class only). The development and application of these age structured models has been reviewed by Usher (1971). Because of the aeging problem, a related model based on **size**-structure has been proposed by Usher (1971) and Lefkovitch (1965).

Further work on length-based models was done by Rosenberg (1988) and Sainsbury (1982a). Shepherd (1987) noted that a transition matrix for updating the length composition of a fish stock at time t to its length composition at time t+1 could be written down directly from the form of the growth

curve. The model is depicted as the Lefkovitch matrix model,



where the population at time T is represented by a population vector $\mathbf{N(T)}$. The entries of the population vector $\mathbf{N(T)}$, $N_i(T)$, represent the number of animals present between sizes i and $i+1$ mm. The population vector at T+1, $\mathbf{N(T+1)}$, is calculated by multiplying $\mathbf{N(T)}$ by a projection matrix $\mathbf{P}$, which contains survivorship factors. Individuals grow into successive size-classes each year, but because growth rates are variable, individuals from size-class i grow into a number of longer size-classes $i+1, i+2 \ldots i+n$, (Getz and Haight 1989), hence the more complex structure of the $\mathbf{P}$ matrix associated with the Lefkovitch matrix compared to that of the modified Leslie matrix. The product $\mathbf{N(T)P}$ is added to a recruitment vector $\mathbf{R}$ in which recruitment into several of the juvenile size- classes occurs.

Methods

A size-based population model

The structure of the size-based model used in this study is identical to that reported by Barkai and Bergh (1990). Due to differing growth rates, males and females are modelled separately. The vectors $\mathbf{N^m(t)}$ and $\mathbf{N^f(t)}$ represent the male and female size structures of the populaton respectively. $N_i^m(t)$, $i = 1, 2, ...204$ and $N_i^f(t)$, $i = 1, 2, ...204$ are the number of males and females present in the population at the beginning of year t, with carapace lengths greater than or equal to i mm and smaller than $i + 1$ mm. Lobsters smaller than 1 mm in carapace length are not treated in this model.

The upper size-class limit was chosen to be equivalent to the largest L_∞ of the three areas, $i = 204$. It is unlikely that a rock lobster with a carapace length larger than 204mm will be part of one of the populations in this study.

The projection matrix

The projection matrices $\mathbf{P^m}$ and $\mathbf{P^f}$ consist of elements $P_{i,j}$ (i represents the column index and j the row index), where each element $P_{i,j}$ gives the proportion of lobsters in size-class i at time t which grow to be in size-class j at time $t + 1$ in the absence of mortality. Over the period t, lobsters grow an average amount (length increment) which is a function of the initial size (Sainsbury 1982). This growth increment will show individual variation, so that at time $t + 1$, lobsters from size-class i at time t are distributed over a range of sizes (Figure 2). $P_{i,j}$ is the proportion of total area under the frequency distribution bounded by the class limits of j, which in the model

are j to $j+1$. In the model reported by Barkai and Bergh (1990) the length increments are beta distributed. Figure 3 illustrates mean increments as a function of length in the model. CEM is the mean growth increment of lobsters at a size of 1mm. At some size, SIM, growth rates reach a maximum (MAX) and start to slow down, and L_∞ is the size at which the growth increment equals zero. Estimated mean growth increments for male and female lobsters are shown in Figures 4 and 5. The adult male growth data for Robben Island used here is the average of growth data from:
(1) Growth data from Pollock (1987)
(2) Heydorn's (1969a) tagging experiments near Robben Island
(3) Sea Fisheries Research Institute growth data for Robben Island (1974/75 – 1976/77, 1986/87 –1989/90 seasons)

The mean growth increments for each size-class from the three sources were added together and divided by three to obtain an average. The associated variances, and maximum possible growth increments of the mean growth increments were assessed from these data. Male growth data for Hout Bay and Dassen Island were obtained from the Sea Fisheries Research Institute data for 1984 –1986. Male and female juvenile and female adult growth data for all areas were obtained from Pollock (1987). As only the male portions of the pristine size frequencies were used in estimating s, the female growth data is not required therefore for this calculation, but is used in catch and biomass calculations.

For the beta distribution for length increment, let x be the quotient of the length increment $l - l_s$ (where l_s is the carapace length of the lobster at the start of the year, and l is the carapace length of the lobster at the end of the year), and the maximum possible length increment $g(l_s)$,

$$x = \frac{l - l_s}{g(l_s)}. \tag{4}$$

The beta probability density for x, denoted $p(x)$ is

$$p(x) = \kappa x^{p-1}(1-x)^{q-1} \quad p,q > 0 \text{ and } 0 < x < 1, \tag{5}$$

where κ is a normalization constant.

The expected value of x, μ_x, is

$$\mu_x = \frac{p}{p+q}, \tag{6}$$

and the variance in x, V_x is

$$V_x = \frac{pq}{(p+q)^2(p+q+1)}. \tag{7}$$

which implies that

$$p = \frac{\mu_x^2(1-\mu_x) - \mu_x V_x}{V_x} \tag{8}$$

and

$$q = \frac{p(1-\mu_x)}{\mu_x}. \tag{9}$$

Entries of the projection matrix are calculated by numerical evaluation of the following integral equations (Barkai and Bergh 1990):

$$P_{i,i} = \int_{l=0}^{l=\frac{1}{2}} (\frac{i-l}{g(i)})^{p-1}(1-\frac{i-l}{g(i)})^{q-1}dl, \tag{10}$$

and

$$P_{i,i+j} = \int_{l=j-\frac{1}{2}}^{l=j+\frac{1}{2}} (\frac{i-l}{g(i)})^{p-1}(1-\frac{i-l}{g(i)})^{q-1}dl, \tag{11}$$

for $j = 1, 2, ..., 204$

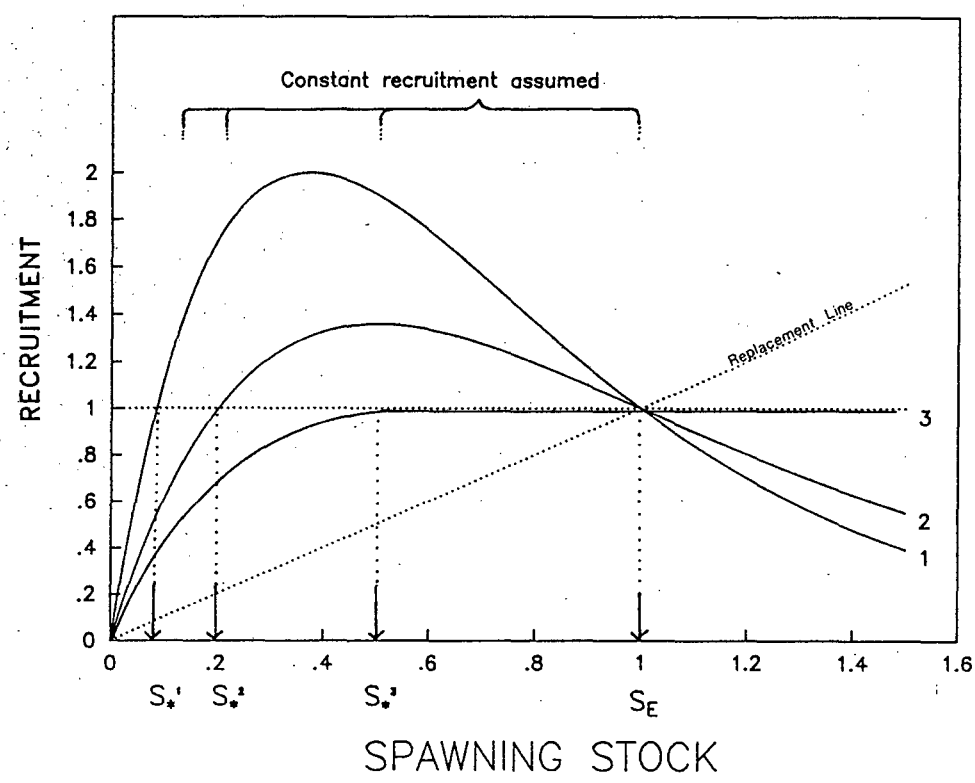
The upper right triangle entries ($P_{i,j}^m$ and $P_{i,j}^f$ for $i = j+1, j+2, ..., 204, j = 1, 2, ...204$) are all zero and therefore exclude the possibility of shrinkage, that is, individuals cannot move to lower size-classes. The diagonal entries are non-zero however, as a small proportion of lobsters do not moult each year, and will therefore remain in the current size-class. Equations (10) and (11) assume that within a size-class i, all animals are at size i.

Natural survivorship and Recruitment

The natural survivorship matrices $\mathbf{S^m}$ and $\mathbf{S^f}$ contain zero entries, except for the diagonal entries which contain the survivorship levels S_i^m and S_i^f for $i = 1, 2, ..., 204$. The model assumes that male and female survivorships are equal. In the model, **RLIM** is the asymptotic survivorship at older ages. Figure 6 illustrates the survivorship – size-class relationship used in the model.

This model assumes that annual recruitment is constant, and occurs in the first fifteen size classes only. The recruitment vector, $\mathbf{R}$, contains this information. The use of constant recruitment models in the stock assessment of lobster populations is common (Ennis 1980; Fogarty 1980; Bannister and Addison 1984; Cambell 1985; Addison 1986). The use of a constant recruitment model in this study is thought to be justified by the following:
i) A number of relationships between the spawning stock biomass and the recruitment for the west coast rock lobster may exist. We can assume however that this relationship is somewhat of the nature of one of the following

curves (from Ricker 1975). For each of the curves, the point where the re-



cruitment curve cuts the replacement line is the level at which the spawning stock is at equilibrium (S_E). In the absence of exploitation, this corresponds to the pristine state of the resource. Through exploitation, the spawning stock is driven to the left of S_E. It is only at a point S_* where recruitment drops below its pristine level. The level of S_* is usually low relative to the pristine S_E level. We can therefore assume that for any of the stock–recruit relatonships that may be representative of the west coast rock lobster (shown above), recruitment an be assumed to be approximately constant for stock sizes that lie within the region $\mathbf{S_E - S_*}$.

ii) Although the west coast rock lobster resource has been depleted to a large extent, most of the fishing mortality has been directed towards the males (as

few females cross the legal size limit). The extent to which the *spawning* stock has been reduced is therefore likely to be relatively small. Estimates of the decline in egg production (relative to the pristine egg production), under various assumptions have been made by Bergh (1990). Egg production can be viewed as an index of the spawning stock biomass. The egg production figures were expressed as a percentage of the pristine level. Under the present 89mm legal size limit (using a discard mortality d=0.075, an s of 0.95, and a fishing mortality level of p=0.3), Bergh calculated the egg% to be 63.07. Depending on the values of d, s, and p that Bergh used in his analysis, the egg% values were found to range from 46.88 to 99.65. From these results one can safely assume the spawning stock biomass to lie at present between $\mathbf{S_E}$ and $\mathbf{S_*}$, and the use of a contant recruitment model is therefore validated.

Dynamics of the size-structured population

The dynamics of the size structure of the pristine population (that is a population that is not being harvested) is modelled as follows:

$$\mathbf{N^m(t+1) = (P^m N^m(t))S^m + R}, \tag{12}$$

and

$$\mathbf{N^f(t+1) = (P^f N^f(t))S^f + R}. \tag{13}$$

Fishing mortality is incorporated into the model via a fishing survivorship matrix $\mathbf{G}$, that is the fishing survivorship matrix consists of diagonal entries e^{-F_i} with zero's everywhere else.

The natural survivorship and fishing matrices are now combined to form the new matrices $\mathbf{H^m}$ and $\mathbf{H^f}$, where $\mathbf{H^m = S^m G^m}$, and $\mathbf{H^f = S^f G^f}$.

The dynamics of the exploited population is therefore:

$$\mathbf{N^m(t+1) = (P^m N^m(t))H^m + R}, \tag{14}$$

and

$$\mathbf{N^f(t+1) = (P^f N^f(t))H^f + R}. \tag{15}$$

Equilibrium Conditions

From (14) and (15), equilibrium numbers for each size-class $i = 1, 2, ...204$ where $\mathbf{E_j^m}$ = the equilibrium number of males in the j^{th} size-class, and $\mathbf{E_j^f}$ = the equilibrium number of females in the j^{th} size-class are given by :

$$E_j^m = \frac{R_j + \sum_{i=1}^{j-1}\left[P_{i,j}^m H_i^m E_i^m\right]}{1 - P_{j,j}^m H_j^m}, \tag{16}$$

and

$$E_j^f = \frac{R_j + \sum_{i=1}^{j-1}\left[P_{i,j}^m H_i^f E_i^f\right]}{1 - P_{j,j}^f H_j^f} \tag{17}$$

for $j \geq 2$,and

$$E_1^m = \frac{R_1}{(1 - P_{1,1}^m H_1^m)} \tag{18}$$

and

$$E_1^f = \frac{R_1}{(1 - P_{1,1}^f H_1^f)}. \tag{19}$$

Fishing gear size selectivity

(Heydorn 1969a, 1969b) reports that larger lobsters chase smaller individuals away from hoop nets. It is possible that this occurs to some degree in traps,

the dominant gear in use today. Furthermore very small lobsters are not retained by either hoopnets or traps. The selectivity function used in this study to reflect this situation is shown in Figure 7.

The mesh size of the traps used to catch lobsters is such that all legally sized lobsters (89mm+) are retained within the traps. For this reason, selectivity was assumed to be size-independent for lobsters with carapace lengths greater than 90mm. Similarly, lobsters smaller than 50mm generally escape retention, and so in the model, lobsters with carapace lengths smaller then 50mm are assumed not to be retained by the nets at all. The proportion of lobsters caught is equal to $\frac{F_i}{M_i+F_i}(1-e^{-F_i-M_i})$, where $M_i = -lns_i$. Due to the software setup, the quantity $Prop_i$ must be defined, where $Prop_i = 1-e^{-F_i}$. $Prop_i$ follows a linear relationship from size 50 to 90, and is a constant maximum value of $PROP$ for i¿90, that is for size-classes 90, 91,...204 ,

$$Prop_i = PROP \tag{20}$$

and for size-classes 50, 51,...89,

$$Prop_i = \frac{(PROP)(i-50)}{40} \tag{21}$$

In the model, the minimum legal catch size (SIZEM) was 89mm, as this conforms to the existing minimum legal size imposed on the west coast rock lobster resource.

At low M_i and high F_i, $Prop_i$ approximates the ratio of catch to initial (start of year) cohort numbers.

Discard mortality

It is assumed that a certain proportion (d) of undersized lobsters (those with a carapace length less than 89mm carapace length), die as a result of being

caught and returned to the sea after sorting. A value of d=0.075 is used here, that is 7.5% of undersized lobsters that are caught and returned to the sea are assumed todie as a result of handling. The value d=0.075, has been accepted as being a realistic value of discard mortality for the west coast rock lobster resource by the Rock Lobster Working Group of the Sea Fisheries Research Institute, South Africa. This value is half the value (d=0.15) which was determined experimentally for the western rock lobster *Panulirus cynus* in Western Australia, by Brown and Caputi (1986). Results of an experiment presently being conducted to estimate d in the fishery off the South African west coast will be available in 1992.

To incorporate discard mortality into the model, the $PROP_i$ values for $i \leq 89mm$ are multiplied by the value of d. The proportion of lobsters that die as a result of fishing (for $i \leq 89mm$) is now $PROP_i.d$. (Note that these lobsters do not contribute to the catch).

Yield – Biomass relationships

As mentioned earlier, values of $Prop_i$ are used to model fishing proportions. The fishing mortality coefficients, F_i, are linked to these values by,

$$F_i = -log(1 - Prop_i) \tag{22}$$

Biomass and yield levels are converted from numbers to weights using the following formulae (Barkai and Branch 1988):

$W_i^m = E_i^m a(i)^b$
and
$W_i^f = E_i^f c(i)^d$

where $a = \frac{1}{1601}$, $b = 2.97$
and $c = \frac{1}{1216}$, $d = 2.89$.

The biomass is calculated at the beginning of the year, whilst the yield is calculated at the end of the year. Therefore,

$$C^m = \sum_{i=89}^{204} W_i^m \left[\frac{F_i}{F_i + M_i}\right]\left[1 - e^{-F_i - M_i}\right] \tag{23}$$

and

$$C^f = \sum_{i=89}^{204} W_i^f \left[\frac{F_i}{F_i + M_i}\right]\left[1 - e^{-F_i - M_i}\right], \tag{24}$$

where $\left[\frac{F_i}{F_i+M_i}\right]\left[1 - e^{-F_i - M_i}\right]$ is the harvest proportion. C^m is the catch of male lobsters, and C^f is the catch of female lobsters in one year. (If M is very small, as it is found to be in this study, then one can see that $Prop_i$ will be very close to the harvest proportion in each size class.)
The Total Yield,$C^{total} = C^m + C^f$.

The equilibrium biomass of the population of legal sized lobsters is,

$$Biomass = \sum_{i=89}^{204} W_i^m + W_i^f \tag{25}$$

It is important to note that in this study the biomass and catch levels that are calculated are not absolute quantities but are calculated in such a way as to be relative to one onother, that is, the **shape** of the surplus production curve is what is important here, not the absolute values. As this model assumes constant recruitment, the calculations are therefore effectively giving yield–per–recruit results. Biomass and yields are therefore scaled as follows:

$$Biomass = Biomass \frac{K_{base}}{K_{unscaled}} \tag{26}$$

and

$$Yield = Yield\frac{K_{base}}{K_{unscaled}} \tag{27}$$

where K_{base} refers to the K for the base case parameter set, and $K_{unscaled}$ refers to the K for parameter values not equal to the base case set.

Base case parameter values

It was decided to use a set of base case parameter values, for each of the three areas, which would be used as a reference point in all analyses (unless otherwise stated). These base case parameter values are shown in Tables 1 and 2. Due to insufficient data females of all three areas are assumed to have the same growth rates.

An equal amount of recruitment (5000) occurs in size-classes $i = 1, 2, ...15$. This value of recruitment is used for all regions. The value of 5000 is arbitrary, as all the values produced in the model are expresses as *relative* values.

Natural survivorship estimation

The size-based model and pristine size structure data were used to estimate adult (legal-sized) natural survivorship, for male rock lobsters in two regions:
(1) Robben Island
(2) Hout Bay
Robben Island was declared a rock lobster sanctuary in 1963, fifty years after the catch size frequency data was collected by Gilchrist in the area. Hout Bay was also declared a rock lobster sanctuary in 1963, twenty years prior to the

collection of the Hout Bay pristine catch size frequency data. It is not known how much recovery the Hout Bay region has undergone since harvesting was stopped. To estimate s, the model was fitted to *pristine* size frequencies for each region, using a least squares regression method. A software program *Amoeba* developed by Press et al. (1986) was used to fit the model to the observed data. The objective function that was minimised was:

$$\sum (f_i^{model} - f_i^{observed})^2 \tag{28}$$

where $f_i^{observed}$ = the *pristine* size frequency, and f_i^{model} = the model fitted size frequency for size class i.

Robben Island

The *pristine* size frequency data upon which the estimate of s for Robben Island was based are obtained from historic catch data contained in reports written by Gilchrist in the early part of this century (Gilchrist 1913, 1914, 1918). Gilchrist's catches were recorded from 1913–1918 and were obtained from experimental hauls made with hoopnets. Hoopnets have important gear selectivity characteristics – they do not restrict the catching of very large lobsters, as the hoopnet diameter is sufficiently wide, but reports have shown that large individuals may chase smaller individuals away from the hoopnet.

The areas sampled by Gilchrist include Robben Island, Woodstock Beach, Milnerton, Green Point, Oudekraal and Clifton, see (Figure 8). Gilchrists hauls were made in depths of 3-16 fathoms (5-30 meters). The *pristine* size frequencies (Figure 9) were obtained by averaging the catch data from 1913-1918. As catch data for males was more extensive, the size frequencies represent the male portion of the population only. The sample size used to

calculate the size–class frequencies was n = 4624. Although the resulting size frequencies were assumed to be pristine, exploitation of rock lobster in the areas of Gilchrist's hauls had begun in the late 19^{th} century, although the extent of this fishing on the population at the time of the hauls is unknown.

Due to the problem of selectivity, only carapace sizes of four inches (102mm) and larger were used in the survivorship estimation. It is nevertheless possible that even these large sizes could be affected by selectivity. The natural survivorship was estimated using size classes of $4, 5, 6, 7,$ and 8 inches. (size class 4 inches refers to lobsters 4 inches and larger, but less than 5 inches.) In a series of sensitivity tests, I estimate s using different portions of the pristine size frequency.

Hout Bay

The *pristine* size frequencies (Figure 10) for Hout Bay were obtained from data contained in Sea Fisheries Research Institute data records on research catches made using traps in Hout Bay between 1983–1986. Although data subsequent to 1986 are available, the post-1986 data show the effects of the research fishing pressure, and therefore cannot be regarded as representative of a pristine population. The use of traps also have selectivity implications as the holes in the traps are only 10cm in diameter, thus perhaps preventing very large lobsters from entering the trap. Once again, due to gear selectivity, only sizes 100mm (4 inches) and greater were used in the natural survivorship estimation, and once again only males are included in the size frequency. The sample size used to calculate the size–class frequencies was n = 10 271. Size-class intervals were however smaller than those used for Robben Island – size-classes were 100mm, 110mm, 120mm and 130mm, that is a size-class interval of 10mm was used. A smaller size–class interval could have been

used for Hout Bay, for example a 5mm interval, but as the size–class interval for Robben Island had been forced to be one inch, it was thought best not to reduce the Hout Bay interval any further, in order to keep the two s estimation procedures as comparable as possible. The pristinity of the Hout Bay population at the time of the data collection is also unknown, as fishing occurred in the area up till 1963, at which time Hout Bay became a rock lobster sanctuary. The degree of recovery is not known, but can be assumed to be virtually complete.

Variances of the natural survivorship estimates were calculated using a bootstrapping method (Butterworth et al. 1989). The following procedure was used:
The model was run once using the observed pristine size frequencies, $f_i^{observed}$.
The residuals, R_i , where

$$R_i = f_i^{model} - f_i^{observed},$$

were then calculated. The model was then run 50 times, but in these runs, the model was fitted not to the original observed frequencies, but to observed frequencies calculated by,

$$f_i^{observed} = f_i^{model} - R_{i,random},$$

where f_i^{model} represents the fitted frequency of the model from the first fit using the original data, and $R_{i,random}$ represents a residual drawn at random with replacement from the original set of residuals, using a uniform random number generator. No negative frequencies were encountered during the

bootstrapping procedure. The 50 s estimates are then averaged to produce a mean, and the 68% and 95% confidence limits are calculated. The variances produced, using only 50 bootstrap replications, were considered to be sufficiently low, and additional replications were therefore not produced as it was felt that these would not supply significantly different variance estimates, or any new information.

Sensitivity Analyses

The natural survivorship estimates were subjected to the following sensitivity tests:

Test 1: The value of L_∞ (the size at which lobsters stop increasing in size) was altered by increasing and decreasing the L_∞ value (Figure 11).

Test 2: The value of SIM was altered by increasing and decreasing the SIM value by a percentage of the base case value (Figure 12).

Test 3: The mean growth increments were altered by +40% to -40% from the base case values (Figure 13). As growth rates are known to vary considerably over time and space, it was thought that this sensitivity test would be of particular importance.

Test 4: The objective function $\sum(f_i^{model} - f_i^{observed})^2$ was altered to $\sum(f_i^{model} - f_i^{observed})^2 f_i^{observed}$, to investigate the effect of downweighting the importance of size-classes with low frequencies (that is, size-classes of the larger lobsters). The objective function was similarly changed to $\frac{\sum(f_i^{model} - f_i^{observed})^2}{f_i^{observed}}$ to investigate the effect of downweighting the importance of size-classes with high frequencies (that is, the size-classes of the smaller lobsters). This test

is important as portions of the pristine size frequency may be either over- or under-represented in the data.

Test 5: The value of the maximum possible growth increment, $g(l_s)$, (see equation 4) associated with the mean growth increment was changed. The mean growth increment curves shown in Figure 13 will therefore each be associated with another curve depicting the maximum possible growth increment for each size class.

Test 6: The value of the variance, V_x, in x was changed.

Test 7: The portions of the pristine size frequency used in estimating s were altered. Due to gear selectivity (and other reasons described in the discussion section), portions of the pristine size frequency may not in fact be representative of a true pristine resource. These tests therefore give an idea of the importance of different portions of the size frequency distribution in estimating s.

A simple direct method to estimate s

There is another simpler way to estimate s using pristine size frequency data. This provides a method for checking the s estimate produced by the size-based model. The s is worked out directly from the pristine size frequency, by assuming that:

$$N_{i+1} = N_i e^{-Mt} \tag{29}$$

where t refers to the time (years) taken for the lobster to grow from size i to size $i+1$. The values for t are calculated using the mean growth increments

shown in Figure 4. Therefore

$$e^{Mt} = \frac{N_i}{N_{i+1}} \tag{30}$$

and thus

$$M = \frac{ln\frac{N_i}{N_{i+1}}}{t} \tag{31}$$

and so

$$s = e^{-M} \tag{32}$$

The population is assumed to be at equilibrium. N_i refers to the number of individuals in size-class i at time t, and N_{i+1} refers to the number of individuals in size-class $i+1$ at time t. For Robben Island, size-classes of 4, 5, 6, and 7 inches are used , and for Hout Bay, size- classes of 100, 110, and 120 mm are used. An average result for each area is obtained over all size-classes.

Harvest proportion estimation – Dassen Island

It has been assumed that the Robben Island and Dassen Island rock lobster populations are sufficiently similar, due to their close geographic proximity, so that these two populations will have very similar natural survivorships. The natural survivorship estimate for lobsters in the Robben Island region can therefore be applied to the Dassen Island lobster population in order to determine the present PROP level of Dassen Island.

A size frequency obtained from a population which has been subjected to fishing will reflect both natural mortality (M) and fishing mortality (F), but one cannot easily distinguish the effects these two mortalities have on the size structure. If one has an s estimate for the population, then the effect F has on

the population size structure can be distinguished. The model was therefore fitted using the s estimate for Robben Island (s=0.94), as the Robben Island s estimate is assumed to apply to lobsters at Dassen Island. The model was fitted to the catch size frequencies obtained from catch data for Dassen Island for the 1983/84 to 1989/90 seasons . This information was supplied by the Sea Fisheries Research Institute. Size-classes of 90mm, 95mm,...130mm were used in the estimation. Size-classes smaller than 90mm were not used due to gear selectivity. The sample size used to calculate the size–frequencies was n = 77 063.

Dynamic calculations

There is currently considerable debate around whether catch levels in the South African rock lobster resource are sustainable, or whether further quota reductions are needed to reach a sustainable management regime. Experience with the Namaqualand portion of the resource suggests that sustainable catch levels may be dramatically smaller than historic levels. It seems crucial that some comment regarding this issue be made for the southern part of the resource, which is presently the economic backbone of the rock lobster industry. A proper analysis needs to be done on historic catch statistics to throw light on this issue. Here, some instructive modelling results are presented as a first step in this process.

An exercise was done in which 50 year projections of yield and biomass levels were made for Robben Island and Hout Bay, where the population at year 1 is assumed to be at a pristine level. The catch and biomass levels are projected according to various PROP scenarios (Figure 27). Projections for a 50 year period are also made for the Dassen Island lobsters, to see the effect that different harvesting policies would have on yield and biomass levels. As

catch and biomass values are not absolute but only relative to one another, this exercise gives only an indication of trends that might result under these different scenarios, rather than making absolute catch and biomass level predictions.

Biomass and yield levels for the dynamic calculations are converted from numbers to weights by once again applying Barkai and Branch's (1988) conversion formulae:

$$WD_i^m(t) = N_i^m(t)a(i)^b \tag{33}$$

and

$$WD_i^f(t) = N_i^f(t)c(i)^d \tag{34}$$

where $WD_i^m(t)$ and $WD_i^f(t)$ refer to the biomass of male and female lobsters respectively, in the i^{th} size class at time t. (see equations 14 and 15) and $a = \frac{1}{1601}$, $b = 2.97$
and $c = \frac{1}{1216}$, $d = 2.89$.

The total biomass of the legal sized population at time t is thus,

$$Biomass(t) = \sum_{i=89}^{204} WD_i^m(t) + WD_i^f(t) \tag{35}$$

The yield in now calculated by:

$$CD^m(t) = \sum_{i=89}^{204} WD_i^m(t) \left[\frac{F_i}{F_i + M_i}\right] \left[1 - e^{-F_i - M_i}\right] \tag{36}$$

and

$$CD^f(t) = \sum_{i=89}^{204} WD_i^f(t) \left[\frac{F_i}{F_i + M_i}\right] \left[1 - e^{-F_i - M_i}\right], \tag{37}$$

where $CD^m(t)$ and $CD^f(t)$ are the catches taken of male and female lobsters resectively, during the year t.

The total yield for year t is therefore,
$CD(t)^{total} = CD(t)^m + CD(t)^f$.

Results

Natural survivorship estimates

Natural survivorships (for adult males) were estimated for Robben Island and Hout Bay, by fitting the size-based model to *pristine* frequencies. The natural survivorship estimate for **Robben Island** is:

s = 0.94.

The 68% confidence limits on this estimate are 0.936–0.946, and the 95% confidence limits are 0.931 – 0.950.

(Unless otherwise stated, s in this study refers to RLIM, the adult male natural survivorship.)

Goodness of fit of the model size frequencies (for Robben Island) for the estimate of $s = 0.94$, and the observed pristine size frequencies, is shown in Figure 14, together with the size frequencies fitted using other values of s.

The natural survivorship estimate for **Hout Bay** is:

s = 0.87.

The 68% confidence limits on this estimate are 0.870 – 0.874, and the 95% confidence limits are 0.868 – 0.876.

Goodness of fit of the model size frequencies (for Hout Bay) for the estimate of $s = 0.87$, and the observed pristine size frequencies, is shown in Figure 15,

together with the size frequencies fitted using other values of s.

Results of the sensitivity analyses

Standard errors were calculated for several of the sensitivity tests, to determine if these would differ significantly from those calculated for the base case. The results showed however, that the standard errors are very similar to those for the base case. For example, the 68% and 95% confidence limits for Test 1 $L_\infty = 170$ (Robben Island) are 0.939–0.949, and 0.936–0.956 respectively. (The base case confidence limits were 0.936–0.946 and 0.931–0.950). The standard errors for Test 7, where different numbers of data points were used in the s estimation, likewise revealed comparable standard errors – for example, the 68% and 95% confidence limits for Test 7 (Robben Island) where only size–classes 7 and 8 inches were used, are 0.934–0.943 and 0.928–0.947 respectively. Standard errors for all sensitivity tests were therefore assumed to be comparable to those calculated for the base case parameter values.

Robben Island

Results of Test 1: The estimate of s is only slightly sensitive to changes in the value of L_∞ (Table 3). The estimate of s increases from 0.940 to 0.947 as L_∞ decreases from 220 to 170.

Results of Test 2: The estimate of s is only slightly sensitive to changes in the value of SIM (Table 4). For SIM values of SIM-50% to SIM+30%, no changes in the estimate occur. For SIM values of SIM+50% and larger, the s estimate increases slightly. When increasing the value of the SIM, the value

of MAX decreases, thus lowering the average growth rate. As the growth rate decreases, the time period for lobsters to move from one size-class to the next increases. This results therefore in a decrease in M (as $e^{Mt} = \frac{N_i}{N_{i+1}}$ where t = time taken to move from size-class N_i to N_{i+1}), and thus the estimate of s increases.

Results of Test 3: The estimate of s is very sensitive to changes in the mean growth increment (Table 5). The estimate of s increases with decreasing growth rates. The s estimate varies from 0.917 (for a 40% increase in the mean growth increment) to 0.968 (for a 40% decrease in the mean growth increment). These estimates are shown more clearly in Figure 16. As with the previous result, the increase in the s estimate with decreasing growth rate can be explained by the virtue of the increased time period to grow from one size-class to the nest with the lowering of the growth rate.

Results of Test 4: The estimate of s is slightly sensitive to changes in the objective function. With the objective function $\sum(f_i^{model} - f_i^{observed})^2 f_i^{observed}$, the estimate is 0.945, that is when the importance of the size-classes of lower frequencies (larger lobsters) is downweighted, the s estimate remains approximately the same. With the objective function $\frac{\sum(f_i^{model} - f_i^{observed})^2}{f_i^{observed}}$ the estimate is 0.927, that is when the importance of the size-classes of the higher frequencies (smaller lobsters) is downweighted, the s estimate decreases.

Results of Test 5: The estimate of s is not sensitive to the changes in the maximum possible growth increment (Table 6).

Results of Test 6: The estimate of s is only slightly sensitive to changes in the variance associated with the mean growth increment. The estimate decreases slightly to 0.939 at a high variance of $2.00\, l - l_s$ (Table 7).

Results of Test 7: The estimate of s is slightly sensitive to the portion of

the pristine size frequency that is used in the estimation. The s estimate decreases as size-classes of larger lobsters are progressively used in the estimation. For example, the s estimate when only size-classes of 4 and 5 inches are used is 0.948, whereas the s estimate when only size-classes of 7 and 8 inches are used is 0.939 (Table 8).

Hout Bay

Results of Test 1: The estimate of s is slightly sensitive to changes in the value of L_∞(Table 9). Once again, the estimate of s increases as L_∞ decreases. The s estimate increases from 0,862 to 0.868 as the value of L_∞ decreases from 140 to 115.

Results of Test 2: The estimate of s is only very slightly sensitive to changes of the value of SIM (Table 10). For SIM values of SIM-50% to SIM+40%, no changes in the estimate occur. For a SIM value of SIM+50% , the s estimate increases slightly to 0.883.

Results of Test 3: The estimate of s is very sensitive to changes in the mean growth increment (Table 11). The s estimate increases with decreasing growth rates. The s estimate varies from 0.808 (for a 40% increase in the mean growth increment) to 0.908 (for a 40% decrease in the mean growth increment). These estimates are shown more clearly in Figure 17.

Results of Test 4: The estimate of s is slightly sensitive to a change in the objective function. With the objective function $\sum(f_i^{model} - f_i^{observed})^2 f_i^{observed}$, the estimate is slightly lower at 0.869. With the objective function $\frac{\sum(f_i^{model} - f_i^{observed})}{f_i^{observed}}$ the s estimate is slightly higher at 0.873 (an opposite result to that of Robben Island).

Results of Test 5: The estimate of s is sensitive to changes in the maximum possible growth increment (Table 12). The estimate increases from 0.852 to 0.871 with increasing values of $g(l_s)$ of $1.5\,l - l_s$ to $3.0\,l - l_s$.

Results of Test 6: The estimate of s is sensitive to changes in the variance associated with the mean growth increment. The estimate decreases from 0.870 to 0.824 with increasing variances of $0.5\,l - l_s$ to $2.5\,l - l_s$ (Table 13).

Results of Test 7: The estimate of s increases slightly as size-classes of larger lobsters are progressively used in the estimation. For example, the s estimate when only size-classes of 100mm and 110mm were used is 0.868, and the s estimate when only size-classes of 120mm and 130mm are used is 0.95 (although this may be an anomalous result, as these size-classes of large lobsters occur at very low frequencies and hence have high variances associated, which may account for this anomalously very high s value) (Table 14). These results are opposite to those obtained for Robben Island.

Results of the simple method of estimating s

The estimate of s for Robben Island using the simple method of estimation, s = 0.97 (Table 15), is slightly higher than the model estimate of s = 0.94. The estimate of s for Hout Bay using the simple method of s estimation, s = 0.88 (Table 16), is however very similar to the model estimate of s = 0.87.

Sustainable Yields

A Schaefer model estimates B_{MSY} to be at 0.5K (Schaefer 1954), whilst the Fox model estimates B_{MSY} to be at about 0.37K. The sustainable yield curves for all three areas show a curve that is very skewed to the right, with B_{MSY} occurring at very low levels relative to K. It is important to note the scale of the axes of these curves, as the $\frac{MSY}{B_{MSY}}$ ratio is very small, indicating an unproductive resource.

Robben Island

The sustainable yield curve for Robben Island is shown in Figure 18. The B_{MSY} level (biomass level at which MSY ocurs) is 0.2K, (where K = the carrying capacity), $\frac{MSY}{B_{MSY}} = 0.10$, and $\frac{MSY}{K} = 0.02$.

The $PROP_{MSY}$ (the PROP value that results in the MSY) is 0.11 (Figure 19). This figure is slightly different to the $\frac{MSY}{B_{MSY}}$ figure, as the catch is not calculated simply by multiplying the PROP with the biomass but by using the catch equation described in the methods section. PROP values greater than 0.11 result in a decreased sustainable yield, but this decrease is relatively small. For example, at a PROP of 0.11, the sustainable yield is 1.85, at a PROP of 0.5 the sustainable yield is 1.47, and at a PROP of 0.9 the sustainable yield is 1.24. PROP values smaller than 0.11 result in substantial reductions in sustainable yield (Figure 19). For example, a PROP of 0.01 results in a sustainable yield of 0.69.

Natural survivorship influences the MSY considerably (Figure 20). Within a range of survivorships of $0.90 \leq s \leq 0.96$, the $\frac{MSY}{B_{MSY}}$ ratios vary from 0.23 (s=0.90) to 0.06 (s=0.96) (Figure 21).

The shape of the sustainable yield curve is only slightly affected by the discard mortality. The MSY values for d equal to 1% and d equal to 20% vary by 9% (Figure 22). The $\frac{MSY}{B_{MSY}}$ value for d equal to 1% is 0.12, and for d equal to 20% is equal to 0.09.

Hout Bay

The sustainable yield curve for Hout Bay, using the estimate s=0.87 (Figure 23), is similar to that of Robben Island, except that the $\frac{MSY}{B_{MSY}}$ proportion is higher at 0.38, $B_{MSY} = 0.16$K, and $\frac{MSY}{K} = 0.06$.

The value of $PROP_{MSY}$ for Hout Bay is 0.41 (Figure 24), which once again is slightly different to the $\frac{MSY}{B_{MSY}}$ value for reasons already explained. As with Robben Island, sustainable yield levels decrease only slightly with increasing harvest proportions over the $PROP_{MSY}$ level, but substantial decreases occur for $PROP$ values smaller than $PROP_{MSY}$.

The sustainable yield curve varies with s. For a change in s from 0.85 to 0.91, MSY decreases by 41% (Figure 25). The B_{MSY} levels change only slightly however, with different s values (within the range of s tested).

The $PROP_{MSY}$ values for s=0.85 to s=0.91 also vary only slightly from 0.31 (s=0.85) to 0.51 (s=0.91) (Figure 26).

Results of yield – biomass relationships

Robben Island

Figure 27 shows four different PROP scenarios. The population is assumed to be in a pristine state in year one. Fishing begins at year two and PROP increases in a linear fashion over time, reaching PROP values of 0.1, 0.2, 0.3 or 0.4 at year 50. This pattern of increasing fishing intensity following the start of a fishery is similar to historic patterns (Barkai and Bergh 1990, Pollock and Shannon 1987). The resulting yields of these four scenarios are shown in Figure 28. The higher PROP values result in higher yields in the first 20 years or so, but by the year 38, the lower PROP of 0.1 produces the greater yield ($PROP_{MSY}$ for Robben Island = 0.1). This indicates that this resource can only sustain high fishing intensities for a fairly limited time span, before the yields start to drop off quite considerably.

The total catches over the 50 year period for the different scenarios are shown in Table 17.

Biomass trends corresponding to these scenarios all show a fairly rapid decrease in biomass over the 50 year period, with the biomass level decreasing faster with increasing PROP values (Figure 29). A PROP of 0.4 results however in a biomass level of 0.04K by the year 50 - thus reducing the population to an extremely low biomass level!

HOUT BAY

Similar PROP scenarios to those for Robben Island were applied to the Hout Bay lobsters, except that the PROP levels were $0.1, 0.2, 0.4$ and 0.7. As before, the population is assumed to be in a pristine state in year one. The projected yields show a slightly different trend to that of Robben Island (Figure 30) with the yield levels decreasing (slightly) only with a PROP of 0.7 (after about 12 years). The yield levels increase sdeadily with time for the other PROP values. Initially PROP of 0.7 has the highest yield, with the $PROP_{MSY}$ (0.4) producing the largest yield only by year 38. These results indicate that the Hout Bay resource can withstand more severe fishing pressures than Robben Island.

Total catches over the 50 year period for the four scenarios are shown in Table 18.

The corresponding biomass trends for these four scenarios are also slightly different to those for Robben Island - the biomass levels decrease more slowly over the 50 years (Figure 31). The decrease is once again faster for higher PROP values.

The Dassen Island harvest proportion

An estimate of the present PROP value for Dassen Island was made by fitting the model to a catch size frequency obtained from catch data for Dassen Island from the 1983/4 to 1989/90 seasons, assuming the estimated s for Robben Island of s = 0.94.

(Remember that the true proportion of biomass harvested, $\left[\frac{F_i}{F_i+M_i}\right]\left[1-e^{-F_i-M_i}\right]$,

is related to the PROP value by $F_i = -log(1 - Prop_i))$.

The estimated harvest proportion, is PROP = 0.35.

The fitted model size frequency for PROP=0.35 and the observed size frequency is shown in Figure 32.

The sustainable yield curve for Dassen Island is very similar to that of Robben Island (Figure 33), which is to be expected as the Robben Island and Dassen Island lobsters have very similar growth characteristics, and the same s estimate for Robben Island was used for Dassen Island. The B_{MSY} level is 0.18K. The value of $\frac{MSY}{B_{MSY}}$ is 0.13, slightly higher than that of Robben Island. The $\frac{MSY}{K}$ ratio is 0.02. These values are similar to those for Robben Island as the same s is used, and the Robben Island and Dassen Island lobsters have similar growth characteristics.

Of the three areas, Hout Bay is the most productive with an MSY three times greater than that for both Robben Island and Dassen Island, but this is clearly heavily dependent on the s estimates. As the natural survivorship decreases the productivity will increase, due to a more rapid turnover rate of the population.

The $PROP_{MSY}$ is 0.13 (Figure 34). The present estimated PROP of 0.35 is therefore 2.7 times larger than the $PROP_{MSY}$. At the present PROP value, the expected sustainable yield is 0.99, only slightly below the MSY of 1.09 (Figure 34). It is not known however how close the present yield is to the sustainable yield level.

Yield and biomass projections for Dassen Island

Assuming a PROP of 0.13 (the $PROP_{MSY}$) is the desired PROP level, one can produce a number of scenarios for reaching this target over the next say 50 years (Figure 35). Two scenarios have been considered in this study:

Scenario (1) The PROP is decreased quickly from its present level of 0.35 to a PROP of 0.13 over the first 10 years. The PROP is then maintained at this $PROP_{MSY}$ level for the next 40 years.

Scenario (2) The PROP is decreased more gradually in a linear fashion to PROP = 0.13 by year 50.

The projected yields for these two scenarios are very different (Figure 36). A reduction in PROP to 0.13 over the next 10 years (scenario 1), leads to a drop in yield from 0.99 to 0.68 (a 30% decrease) by the year 12. Yield then increases to a yield that is equivalent to that being harvested at present (0.99) by the year 22. After year 22, the yield continues to rise above the present yield level, reaching MSY by year 50.

By decreasing PROP slowly for 50 years from 0.35 (present PROP) to 0.13 ($PROP_{MSY}$),(scenario 2), the yield decreases slightly over the first 10 years, then increases slightly over the next 17 years, and finally decreases to 0.91 by the year 50. The MSY is only reached at some stage in the future (after year 50) (Figure 36).

The corresponding biomass trends for these two scenarios (Figure 37) show how the population biomass increases rapidly to the B_{MSY} level for scenario 1, and increases more slowly to a level below B_{MSY} for scenario 2.

Total catches over the 50 year period are:
Scenario 1: Total Catch = 49
Scenario 2: Total Catch = 48.
Although scenario (1) produces a very similar total catch over the 50 year period to scenario (2), the drop in yield in the first 10 years (for scenario 1) is significant, and would probably cause the industry to collapse. If the present harvest is sustainable (under a PROP of 0.35), then the total catch over the next 50 years will be equal to 49 (provided the PROP remains constant). This may suggest that with respect to maximising yield over the next 50 years, no change in PROP is necessary for Dassen Island. There are however some economic factors which must be considered.

CPUE (catch-per-unit-effort) is proportional to the biomass. As the biomass decreases therefore, the CPUE will also decrease. The costs of fishing are however inversely proportional to the biomass (as is is harder and more expensive to catch lobsters at a low density). Figure 41 illustrates how the costs associated with fishing increase as the biomass of the stock decreases. A bioeconomic equilibrium biomass, B_E, exists at which point the revenue from the yield equals the cost of obtaining that yield. This is clearly a break-even point, and an uneconomic biomass level to be at. There also exists a biomass level, B_{MAX}, at which rent is maximised (rent = revenue - cost). This B_{MAX} biomass level is clearly an economically optimum level. Although the cost curve associated with Dassen Island is not known exactly, it is likely to be similar to that in Figure 41, that is it will cut the revenue curve at a biomass level to the left of both B_{MSY} and B_{MAX} (as the present PROP is higher than $PROP_{MSY}$). It would thererfore make economic sense to reduce the present PROP in order to increase the biomass level to a point somewhere closer to B_{MAX} (or even B_{MSY}).

Discussion

Feasibility of the natural survivorship estimates

The natural survivorship estimated in this study for the Robben Island region, s = 0.94, is similar to that obtained by Barkai and Bergh (1990) for Zone A. Barkai and Bergh's estimate for Zone A was s=0.93–0.98 (68% confidence limits). The natural survivorship estimate for Robben Island using the simple method estimate, s = 0.97 (Table 15), is slightly higher than the model estimate. In terms of M however, the model estimate (M=0.06) is in fact two times larger than the simple method estimate (M=0.03).

It must be noted that in this study, both estimates of s rely on fewer than five data points, although these data points represent large sample sizes.

The model estimate of natural survivorship for Hout Bay, s = 0.87, is an unexpected result, as it is smaller than Robben Island estimate. The simple method s estimate for Hout Bay was similarly low at s = 0.88 (Table 16). Although these low s estimates for Hout Bay may be due to the growth data (where the L_∞ is far lower than that for the other regions) and size structure information used for the region , there are other possible reasons that could explain these low s estimates.

The survivorship estimates are dependent on three key assumptions. These are reviewed brifly below.

(1) *The observed pristine catch size frequency reflects that of a pristine population.*

One would expect a pristine size frequency distribution to show an accumulation of large individuals, due to the high s and low growth rate associated with these lobsters. This is the case for Gilchrist's historic pristine size frequencies, but not so for the pristine size frequencies used for Hout Bay, where there does not appear to be an abundance of very large (and old) lobsters in the population.

Pollock (1987) calculated a size frequency distribution for Robben Island lobsters that was to represent an unfished pristine population (Figure 38) – the island had been closed to fishing for more than 10 years ! The Robben Island population had been sampled intensively from 1972–1974. Pollock's size frequency, like that of Hout Bay, does not show a large build up of very large lobsters either.

The observed pristine size frequencies used in this study may not be fully representative of a true pristine population for the three following reasons:

(i) The population had not had sufficient time to recover fully to its pristine state, by the time the catch samples were made, and the size frequencies may reflect mortality due to fishing (F) as well as natural mortality (M).

This is likely to be true for the Hout Bay population. This population had been left for about 20 years after fishing was stopped to recover before the research catch samples were taken. As the resulting size frequencies are somewhat different from those of Gilchrist's, one can perhaps assume that rock lobster require a very long period (certainly longer than 20 years) before they recover fully to their original pristine state, with an accumulation

of large sized lobsters. Once fishing is stopped, the population reverts back to its pristine state slowly. Lobsters in the younger size-classes recover first and move progressively up into size-classes of larger lobsters untill the entire population has recovered.

One can therefore expect the Hout Bay s estimate to reflect F as well as M. The Hout Bay model estimate of M = -log s = 0.056 will therefore be a value somewhat higher than that for a truly pristine population. The true natural survivorship for Hout Bay will therefore be one slightly higher than 0.87 (depending on the value of F that must be substracted from the M).

Although Gilchrist's catches were made at a time by which a fair amount of lobster fishing in the area had occurred (for example the Cape Canning Company at Mouille Point caught 842 000 lobsters in the 1894/95 period), the population was closer, in time, to its original pristine state. It is however likely that the true pristine population would reflect an even larger build up of large sized individuals than Gilchrist's size frequency has shown.

Although the Robben Island and Hout Bay areas have been regarded as pristine, the very oldest lobsters in these areas may still reflect F (from the days of intense fishing before the areas became reserves). The size–classes that are therefore most likely to reflect F as well as M are those of the very large (and old) lobsters. By estimating s using a pristine size frequency without these size-classes, a larger s estimate should be produced. This appears to be the case for Robben Island, where the results of sensitivity test 7 have shown the s estimate to increase slightly as size-classes of smaller lobsters are progressively used in the estimation. Results of sensitivity test 4, where the objective function is changed, support this result. When the objective funtion is used that downweights the importance of size-classes with lower frequencies (the larger lobsters), the s estimate increases. When the

objective function is used that downweights the importance of size-classes with higher frequencies (the smaller lobsters), the s estimate decreases.

Results of the simple method of s estimation similarly show a decrease in the s estimate as size-classes of larger lobsters are used (Table 15) in the s calculation.

The s estimate for Hout Bay does not however follow these expected results. Results of sensitivity test 7 do not show a clear increase of the s estimate as size-classes of smaller lobsters are progressively used in the s estimation. Results of sensitivity test 4 actually show an opposite result to that for Robben Island, with the s estimate decreasing slightly as the importance of size-classes with lower frequencies (larger lobsters) is downweighted. Results of the simple method of s esimation show no clear correlation with respect to the size-class used in the s estimation. The pristine size frequency for Hout Bay is still likely to be one that represents a population that has not fully recovered from an exploited state. Other factors may be influencing the size frequency distribution.

(ii) The pristine size frequency may be influenced by the gear used in obtaining the catch data. Gilchrist's data was based on catches made with hoopnets wich had a 39 inch diameter. It has been noted (Heydorn 1969b) that larger individuals chase smaller ones away from the hoopnets by agressive behaviour. For this reason, Gilchrist's size frequency may underestimate smaller lobsters. If this is the case, results of this study show a slightly lower s estimate when the size-classes of smaller lobsters (the size-classes that are likely to be misrepresented) are downweighted or removed from the estimation.

The pristine size frequency for Hout Bay was obtained from catches made using traps. These traps have holes of 10cm diameter which allow the lobsters

into the trap. The possibility therefore exists that extremely large lobsters may be excluded from the traps by being too large to fit through these holes. If this is the case then the Hout Bay pristine size frequency would underestimate the very large lobsters, and one should therefore expect the true s to be larger (than has been estimated in this study) as the true pristine size frequency should have a greater build up of very large old lobsters. Results in this study do not however substantiate this possible phenomenon.

(iii) The fishing gear selectivity function used in this study (Figure 7) may not be entirely correct. It has been assumed that all lobsters 90mm and larger are totally selected. This may not be the case, and lobsters greater than 90mm may not in fact be totally selected. The size-classes of the smaller lobsters (within this range) would therefore be underestimated. Results for Robben Island indicate that the s estimate decreases slightly when the size-classes of smaller lobsters are removed from the s estimation or these size-classes (which have high frequencies) are downweighted.

(2) *Natural mortality of lobsters may not be constant over time.*

In this study, it has been assumed that M is constant over time. This may not be true, as natural mortality is likely to be density dependent (Pollock 1987). Mortality rates are likely to increase in areas of overcrowding due to food and space limitations (Pollock 1987).

(3) *Growth increments of lobsters are not constant.*

The growth rates of lobsters are not constant, they vary considerably over time and space (Heydorn 1969a, Pollock 1981, Pollock 1987). Growth rates

are likely to decrease with increasing density, due to food shortage. The model has assumed that the present growth rates used in the s estimations are applicable to past pristine size frequencies. This is not likely to be true. The population biomass levels in historic times are likely to have been at much greater levels than at present. This could indicate the presence of **lower** growth rates in the past. The results of this study have shown that decreased growth rates result in an even **higher** s estimate than the present model estimate. On the other hand, historic natural mortality rates could also have been **higher** due to overcrowding and food shortage, and this would indicate a **lower** s than the model estimate. Clearly all these assumptions are relevant and must be considered when assessing the natural survivorship estimates.

Sensitivity of the s estimates to growth parameters and size frequency information

Results of the sensitivity tests for both the Robben Island and Hout Bay s estimate show that the s estimates are slightly sensitive to most of the parameters tested, and are extremely sensitive to the growth rates assumed. As growth rates do vary considerably over space and time, this result has important implications as the natural survivorship of rock lobsters is likely to change from region to region and over time.

Although only a few data points are used in the s estimation, the s estimates appear to be somewhat sensitive to precisely which portion of the pristine size frequency is used to estimate s. The Robben Island s estimate increases as size-classes with high frequencies (the smaller lobsters) are downweighted

or removed from the s estimation. The Hout Bay s estimatation produces an opposite result (to that of Robben Island), with the s estimate decreasing slightly as size-classes with high frequencies (the smaller lobsters) are either downweighted or removed in the s estimation. These results indicate that it is important to understand and recognise the possible errors that may exist in the pristine size frequency distribution. Certain portions of the distribution are likely to be either over- or underestimated, and this can thus effect the result of the s estimation. As size-classes with low frequencies are associated with high variances, the estimates of s produced when using these size-classes must be analysed with these variances in mind, and one can therefore expect to find some rather different results when using these size-classes.

Relationships between biomass and sustainable yield

The sustainable yield curves for all three areas show MSY at very low biomass levels (relative to K). B_{MSY} ranges from 0.20K (Robben Island) to 0.16K (Dassen Island). This means that the population would have to be fished down to very low levels (relative to K) in order to reach MSY. The implications of these low B_{MSY} values forces one to evaluate the feasibility of MSY as a management goal. Forcing a population to such low levels (to reach MSY) can be dangerous. Due to errors (process or observation), either the target B_{MSY} may in fact be lower than the true B_{MSY}, or the population may be mistakenly reduced to a level below B_{MSY} due to overfishing or unreported catches. Once a population is driven past the B_{MSY} level, especially if B_{MSY} is at such a low level as it is for these three areas, the population may be forced to a level from which it cannot recover and the population may therefore collapse if the fishing intensity continues at a high rate. As mentioned earlier, economic factors must also be considered. Although MSY can be take by fishing the population down to its very low B_{MSY} level, fish-

ing operations become very costly at these low bomass levels. It would make more economic sense therefore to fish the population at a higher biomass level, even though a yield somewhat smaller than MSY would be harvested. This will require however that yields must be reduced untill such time as the biomass level has recovered to a more economically viable level.

Discard mortality is an important factor when considering sustainable yield levels. Although the handling of undersized lobsters may result in death (discard mortality), this handling has also been shown (Brown and Caputi 1986) to cause a reduction in growth of the returned lobsters at the first moult after exposure - in both field and laboratory trials. This reduced growth could have several consequences (Davis 1981):
(1) The undersized lobsters remain below legal size for longer and are therefore subjected to additional natural mortality and a greater degree of multiple capture and handling.
(2) The affected animals entering the fishery at a smaller size will reduce the harvestable yield. The value of d = 0.075 used in this study is a conservative one. Barkai and Bergh (1990) used a value of d = 0.15 in their study of Zone "A" rock lobsters, and it was pointed out in their report that the true value of d could be much larger than 0.15. An increased value of d could have severe implications for the west coast rock lobster resource. An increase in d would imply a reduction in the sustainable yield which could result from reduced growth rates, reduced egg production or an increase in natural mortality.

The total catches over the 50 year period for all three scenarios discussed, are very similar, although total catches for the first 10 years are very different. Scenario (1) results in very reduced catches in the first 10 years which is likely to cause a collapse of a fishing industry. The highest total catch (for the 50 year period) occurs in fact if the present PROP of 0.35 is maintained (as-

suming that the present yield is at a sustainable level already). With respect to maximising yield, results of this study would support the maintenance of the present PROP at Dassen Island. This needs to be confirmed however by comprehensive dynamic analyses using all available historic catch statistics.

One needs however to consider short term versus long term gains, as well as costs, when considering management policies. From an economic point of view, the biomass should be increased to a level closer to B_{MSY} or B_{MAX}. The PROP at Dassen Island is at present about three times greater than the $PROP_{MSY}$. If the MSY strategy is to be implemented for Dassen Island, PROP must be decreased. This will result in short term yield losses, but after 50 years the MSY will be reached, and the biomass level will have recovered to a more economically (and biologically) healthy level. The MSY strategy for Dassen Island will not result in greater total yield over the next 50 years, but will reduce fishing costs as the biomass level increases. One needs however to consider the loss in earnings as the fishing intensity (and hence yield) is reduced. Unemployment may also result as the fishing capacity is reduced.

The projected yields for the pristine Robben Island population have a very similar pattern to historic lobster catches in the Western Cape sectors (Figure 39, Pollock and Shannon 1987). These show a period of increasing catch at the beginning of the harvesting which drop off and then level out after about fifteen to twenty years (compare Figures 28 and 39).

The sustainable yield curves for Robben Island (Figure 19) , Hout Bay (Figure 24) and Dassen Island (Figure 34) show slightly different shapes to the sustainable yield curve that Barkai and Bergh (1990) produced (Figure 40) for Zone A using an s estimate of 0.96. Barkai and Berghs's curve drops of very quickly once the PROP passes the $PROP_{MSY}$ level (of 0.06). A value of PROP = 1 means that only sizes of 90mm and greater are caught at this

proportion (Figure 7). Sizes below 90mm are caught with a lower proprtion. As catches are calculated at the end of the year, the biomass has time to grow (with only M operating) until the end of the year, when the biomasses are projected to the beginning of the next year and then calculated.

PROP changes are far more critical at low PROP values, where even slight decreases in PROP result in quite significantly large decreases in sustainable yield. It must be remembered however that these low PROP's (although influencing the sustainable yield significantly) are leaving the biomass level on the safer side of B_{MSY}, and therefore will keep the population at a healthier level, as well as reducing the costs of fishing.

The s estimate affects the $PROP_{MSY}$ level to a certain degree. The $PROP_{MSY}$ levels for Robben Island under the range of
$0.90 \leq s \leq 0.96$ vary from 0.06 to 0.24. If the s cannot be reliably estimated, one can still reach MSY values by maintaining PROP's within this range (assuming s is not larger than 0.96 or smaller than 0.90). The problem exists however, that if for example, one assumes s to be 0.90, and hence the $PROP_{MSY}$ value to be 0.24, when in fact the true s value is 0.96 which has a $PROP_{MSY}$ value of 0.06, a *maximum* sustainable yield (of 1.25) will not be obtained, but rather a lower yield of approximately 1.01 will be caught.

In this study only one value of the effective minimum legal size was considered, that being 89mm – the present minimum legal size enforced for the west coast rock lobster fishery. Further studies should be conducted to investigate the implications of lowering (or raising) the present minimum legal size.

Productivity of the South Arican rock lobster resources

The productivity of the rock lobster resources is low but spatially variable. The $\frac{MSY}{B_{MSY}}$ values range from 0.10 (Robben Island) to 0.38 (Hout Bay). Hout Bay appears therefore to be the most productive of the three areas, even though it has a lower natural survivorship associated with it. Although Hout Bay's MSY is three times that of Robben Island's (relative to the unexploited K), the MSY of Hout Bay can only be reached by applying a greater PROP of 0.41 that is, the PROP needed to reach MSY for Hout Bay is roughly four times that of $PROP_{MSY}$ for Robben Island. As mentioned earlier, the productivity of the Hout Bay resource depends heavily on the s estimate. It must be noted that the west coast rock lobster resource cannot be treated as one single resource or managed therefore as a whole. It appears that within even quite close geographic proximity, lobster populations have rather different growth characteristics and natural survivorships. Research has shown that little migration occurs from region to region, therefore enforcing the isolation of individual populations.

The implications of a high s for a rock lobster resource

The high natural survivorsip estimate of s=0.94 for Robben Island has important implications. As mentioned previously, a high s scenario results in a large unexploited biomass. Initially therefore, large yields can be taken from the accumulated standing stock. However since yields cannot be sustained, if fishing continues to occur at levels reached prior to stock depletion, the population will be reduced to extremely low levels, and may even collapse.

It is important to note the very long time scales invoved in the dynamics of this resource. Due to the very low growth rates and high natural sur-

vivorships, turnover rates of the population are slow. When managing this resource, this fact must be kept in mind, as any new regulations or methods aimed at influencing the population size will take time to be manifested throughout the population.

The drastic yield reductions that have occurred in Zone A are apparently due to the inherently high value of s. Although stocks further south have not been depleted to such an extent, results of this study have shown that lobsters in the Robben Island region similarly have a high s, which suggests that the process that has already occurred in Zone A may occur in the South too, if fishing intensities continue at their present rate.

Conclusion

Natural survivorship for Robben Island lobsters has been estimated to be 0.94.

Natural survivorship for Hout Bay lobsters has been estimated to be 0.87.

These estimtes of s are highly sensitive to the growth rates of the lobsters, and to the size frequency information used.

The present PROP for Dassen Island is estimated to be 0.35.

The B_{MSY} level for all three regions is low.

Robben Island: 0.20K

Hout Bay: 0.20K

Dassen Island: 0.20K

The $\frac{MSY}{B_{MSY}}$ ratios are:

Robben Island: 0.10

Hout Bay: 0.38

Dassen Island: 0.13

The $\frac{MSY}{K}$ ratios are:

Robben Island: 0.02

Hout Bay: 0.06

Dassen Island: 0.02

The high s scenario results in a large unexploited biomass. This biomass

can support very large yields at the onset of fishing. The biomass level can however be drastically reduced if these initial high catches are maintained.

The west coast rock lobster resource cannot be treated or managed as a whole. Several populations are likely to exist, each with a slightly different natural survivorship and diferent growth characteristics.

Due to the very slow growth rates of the lobsters, long time scales are involved with respect to the dynamics of the populations.

The use of pristine size structure information to estimate s, is limited by the availability of reliable pristine size structure data and by the availability of matching growth information.

A variety of dynamic estimation procedures exist, which do not assume equilibrium conditions, which may be feasible methods for estimating s. These procedures would involve dynamic non–linear regressions using information on the catch, effort and catch size structure available in each area over the history of the fishery. Such calculations have been performed for lobsters in Zone A (Bergh and Barkai, in prep), and similar calculations could be carried out for other rock lobster fishing areas.

Glossary

B : The sustainable biomass of the population.

B_{MSY} : The biomass level at which the maximum sustainable yield (MSY) occurs.

B_E : The biomass level at which the revenue obtained from the yield equals the costs needed to obtain the yield.

B_{MAX} : The biomass level at which maximum rent occurs.
(Rent = revenue-costs).

C^m : The sustainable catch or sustainable yield of male lobsters available in one year.

C^f : The sustainable catch or sustainable yield of female lobsters available in one year.

C^{total} : The total sustainable yield available in one year ($C^{total} = C^m + C^f$).

$CD^m(t)$: The catch of male lobsters taken in year t (used in dynamic calculations).

$CD^f(t)$: The catch of female lobsters taken in year t (used in dynamic calculations).

$CD^{total}(t)$: The total catch taken in year t (used in dynamic calculations).

CEM : The mean growth increment of lobsters in size-class 1mm.

CPUE : The catch-per-unit-effort.

d : Discard mortality – the proportion of undersized lobsters that are caught and returned to the sea that die as a result of handling.

E_i^m : The number of male lobsters in size-class i under equilibrium conditions.

E_i^f : The number of female lobsters in size-class i under equilibrium conditions.

f : A superscript which qualifies a variable to refer to female rock lobsters.

f_i^{model} : The fitted model frequency for lobsters in size-class i.

$f_i^{observed}$: The observed size frequency for lobsters in size-class i.

F : Fishing mortality – the fishing mortality coefficient defines how fast a population decreases in size due to deaths caused by fishing.

F_i^m : Fishing mortality for male lobsters in size-class i.

F_i^f : Fishing mortality for female lobsters in size-class i.

G^m : The fishing matrix for male lobsters.

G^f : The fishing matrix for female lobsters.

$g(l_s)$: The maximum possible growth increment associated with the mean growth increment of lobsters.

H^m : The matrix incorporating survivorship from natural mortality and fishing mortality for male lobsters ($H^m = S^m F^m$).

H^f : The matrix incorporating survivorship from natural mortality and fishing mortality for female lobsters ($H^f = S^f F^f$).

i : An index which refers to the size-class. Size-class i contains individuals with carapace lengths of $i$mm and greater, but less than $i + 1$ mm.

j : An index which refers to the size-class into which lobsters grow (see $P_{i,j}$).

K : Carrying capacity – the carrying capacity of any living reaource is the biomass level the resource will have under unexploited pristine conditions. The K in this report refers to the unexploited biomass level of lobsters of 89mm and larger.

K^{base} : The carrying capacity for the populaton with base case parameter values.

$K^{unscaled}$: The carrying capacity for the population under parameter values that differ from the base case set.

l : The carapace length of lobsters at the end of the year.

l_s : The carapace length of lobsters at the start of the year.

$l - l_s$: Carapace length increment of lobsters.

ln : Natural logarithm.

L_∞ : The size at which growth is reduced to zero.

M : Natural mortality – a natural mortality coefficient defines how fast a population decreases due to deaths caused by natural processes.

M_i^m : Natural mortality for male lobsters in size-class i.

M_i^f : Natural mortality for female lobsters in size-class i.

m : A superscript which qualifies a variable to refer to male rock lobsters.

MAX : The maximum growth increment (corresponds to the size of SIM).

MSY : Maximum sustainable yield – the maximum amount that can be harvested from a population on an indefinite basis, without changing the population size.

N(t) : The number of individuals present in the population at the beginning of year t.

$N_i^m(t)$: The number of males in size-class i present in the population at the beginning of year t.

$N_i^f(t)$: The number of females in size-class i present in the population at the beginning of year t.

P^m : The projection matrix for males – used for projecting the number of male lobsters from one size-class to the next each year as a result of growth.

P^f : The projection matrix for males – used for projecting the number of female lobsters from one size-class to the next each year as a result of growth.

$P_{i,j}$: An element of the projection matrix – refers to the number of individuals in size-class i that grow to be in size-class j each year.

p(x) : The beta probability density for x.

$Prop_i$: This has the value of $1 - e^{-F_i}$ for lobsters in size-class i.

$PROP$: The constant maximum value of $Prop_i$ for $i > 90$.

$PROP_{MSY}$: The PROP value that results in MSY.

R : The recruitment vector.

R_i : The number of lobsters recruited into size-class i.

RLIM : Refers to the adult (legal sized) natural survivorship.

s : Natural survivorship – the proportion of individuals that survive natural mortality from one year to the next. Unless otherwise stated, s refers to adult (legal sized) lobsters. ($s = e^{-M}$).

S^m : The natural survivorship matrix for males.

S^f : The natural survivorship matrix for females.

S_i^m and S_i^f : The proportion of lobsters in size-class i that survive natural mortality from one year to the next.

SIM : Refers to the size at which growth rates of lobsters start to decrease.

SIZEM : The minimum size of lobsters that can be legally caught.

T or t : Time at the beginning of a year.

V_x : The variance in x.

W_i^m : The equilibrium biomass of male lobsters in size-class i.

W_i^f : The equilibrium biomass of female lobsters in size-class i.

$WD_i^m(t)$: The biomass of male lobsters in size–class i at time t (used in dynamic calculations).

$WD_i^f(t)$:The biomass of female lobsters in size–class i at time t (used in dynamic calculations).

x : The quotient of the length increment $l - l_s$ and the maximum possible length increment $g(l_S)$.

μ_x : The expected value of x (the mean growth increment for lobsters).

κ : Normalisation constant used in calculating the beta probabilty density for x.

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Table 1: Robben Island base case parameter values (mm) used in the s estimation, and catch and biomass calculations.

Parameter	males	females
L_∞	204	106
SIM	55	50
CEM	2.48	4.24
MAX	5.70	4.24
Growth increment of a 100mm lobster:	4.02	0.33
Growth increment of a 90mm lobster:	4.41	0.63
V_x	0.55 μ_x	0.24 μ_x
$g(l_s)$	2.5 $(l - l_s)$	2.0 $(l - l_s)$ + 0.5
(d)	0.075	0.075

Table 2: Hout Bay and Dassen Island base case parameter values (mm) for males, used in the s estimation and catch and biomass calculations (female data the same as for Robben Island females).

Parameter	Hout Bay Males	Dassen Island Males
L_∞	124.5	186.5
SIM	70	50
CEM	2.48	2.48
MAX	6.55	5.50
Growth increment of a 100mm lobster:	2.94	3.61
Growth increment of a 90mm lobster:	4.41	3.63
V_x	1.0 μ_x	0.55 μ_x
$g(l_s)$	2.5 $(l - l_s)$	2.5 $(l - l_s)$
(d)	0.075	0.075

Table 3: Results of sensitivity test 1 for Robben Island lobsters, where the value of L_∞ is changed from the base case value.

L_∞	s estimate
170	0.947
180	0.945
190	0.942
220	0.940

Table 4: Results of sensitivity test 2 for Robben Island lobsters, where the value of SIM is changed from the base case value by a percentage increase or decrease.

SIM	s estimate
SIM - 50%	0.942
SIM - 30%	0.942
SIM + 30%	0.942
SIM + 50%	0.943
SIM + 75%	0.948
SIM(2)	0.954

Table 5: Results of sensitivity test 3 for Robben Island lobsters, where the value of the mean growth increments are changed from the base case values by a percentage increase or decrease.

% change to mean growth increment	s estimate
+40%	0.917
+30%	0.923
+20%	0.930
+10%	0.936
-10%	0.949
-20%	0.955
-30%	0.962
-40%	0.968

Table 6: Results of sensitivity test 5 for Robben Island lobster, where the value of the maximum possible growth increment $g(l_s)$ associated with the mean growth increment is changed from the base case value.

$g(l_s)$	s estimate
1.5 $(l - l_s)$	0.941
2.0 $(l - l_s)$	0.941
2.5 $(l - l_s)$	0.941
3.0 $(l - l_s)$	0.941
4.0 $(l - l_s)$	0.941

Table 7: Results of sensitivity test 6 for Robben Island lobsters, where the value of the variance V_x in x is changed from the base case value.

V_x	s estimate
0.25 μ_x	0.941
0.40 μ_x	0.941
0.55 μ_x	0.941
0.75 μ_x	0.941
1.00 μ_x	0.941
1.50 μ_x	0.940
2.00 μ_x	0.939

Table 8: Results of sensitivity test 7 for Robben Island lobsters, where different portions of the pristine size frequency are used in the estimation of s.

Size classes used (inches)	s estimate
4 5	0.948
4 5 6	0.946
4 5 6 7	0.944
4 5 6 7 8	0.944
5 6 7 8	0.944
6 7 8	0.942
7 8	0.939

Table 9: Results of sensitivity test 1 for Hout Bay lobsters, where the value of L_∞ is changed from the base case value.

L_∞	s estimate
115	0.868
120	0.851
130	0.863
140	0.862

Table 10: Results of sensitivity test 2 for Hout Bay lobsters, where the value of SIM is changed from the base case value by a percentage increase or decrease.

SIM	s estimate
SIM - 50%	0.871
SIM - 40%	0.871
SIM - 30%	0.871
SIM + 30%	0.871
SIM + 40%	0.871
SIM + 50%	0.883

Table 11: Results of sensitivity test 3 for Hout Bay lobsters, where the mean growth increments are changed from the base case values by a percentage increase or decrease.

% change to mean growth increment	s estimate
+40%	0.808
+30%	0.824
+20%	0.839
+10%	0.855
-10%	0.885
-20%	0.900
-30%	0.914
-40%	0.908

Table 12: Results of sensitivity test 5 for Hout Bay lobsters, where the value of the maximum possible growth increment $g(l_s)$ associated with the mean growth increment is changed from the base case value.

$g(l_s)$	s estimate
1.5 $(l - l_s)$	0.852
2.0 $(l - l_s)$	0.866
2.5 $(l - l_s)$	0.871
3.0 $(l - l_s)$	0.871

Table 13: Results of sensitivity test 6 for Hout Bay lobsters, where the value of the variance V_x assocciated with the mean growth increment is changed from the base case value.

V_x	s estimate
0.5 μ_x	0.870
0.8 μ_x	0.871
1.0 μ_x	0.871
1.1 μ_x	0.869
1.5 μ_x	0.861
2.0 μ_x	0.844
2.5 μ_x	0.824

Table 14: Results of sensitivity test 7 for Hout Bay lobsters where different portions of the pristine size frequency are used in the estimation of s.

Size classes used (mm)	s estimate
100 110	0.868
100 110 120	0.870
100 110 120 130	0.872
110 120 130	0.871
120 130	0.950

Table 17: Total catches over the 50 year period for Robben Island under four different PROP scenarios (Catch values are relative but arbitrary).

PROP	Total Catch
0.1	113
0.2	136
0.3	143
0.4	146

Table 18: Total catches over the 50 year period for Hout Bay under four different PROP scenarios (Catch values are relative but arbitrary).

PROP	Total Catch
0.1	14
0.2	19
0.4	23
0.7	25

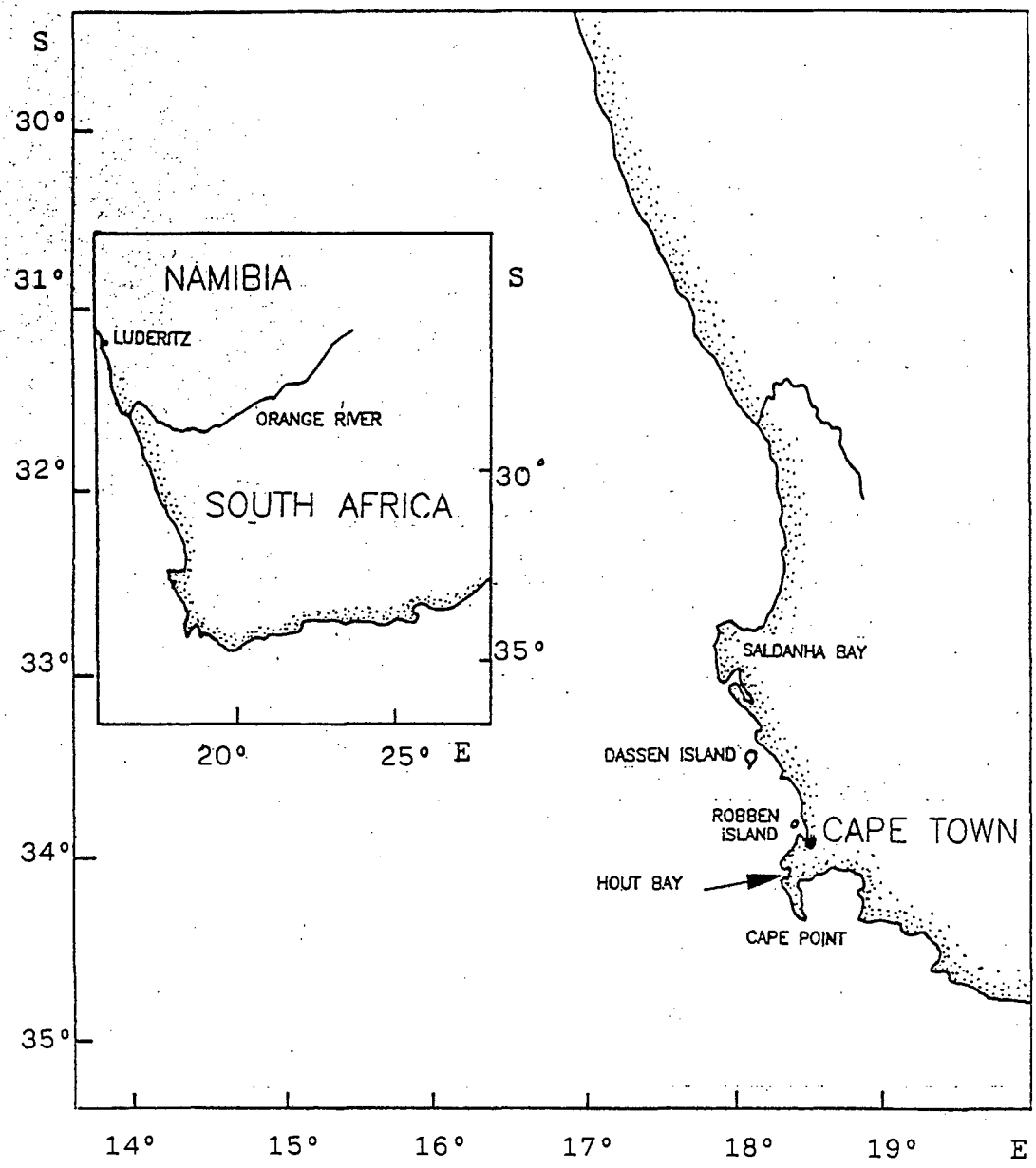

FIG.1: The Cape West Coast showing study areas with the southern African coastline (inset)

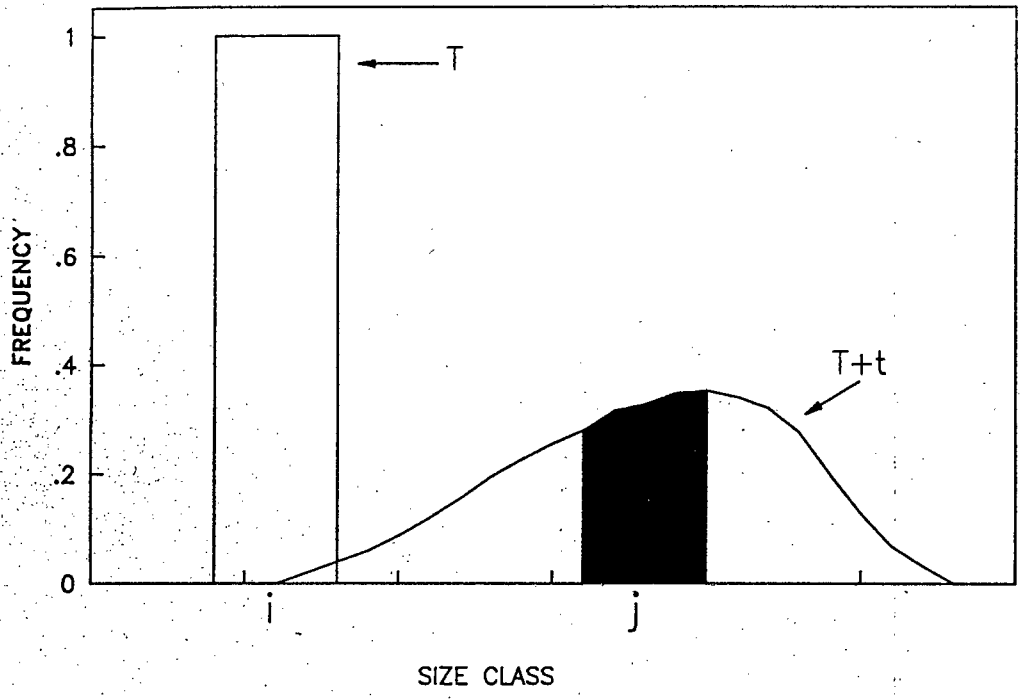

FIG.2: The effect of growth over a period t on the frequency distribution of animals initially in size class i. The shaded area, as a proportion of the total area under the (T+t) curve, is the probability of an animal from class i at T growing to class j at (T+1) (Sainsbury 1982a)

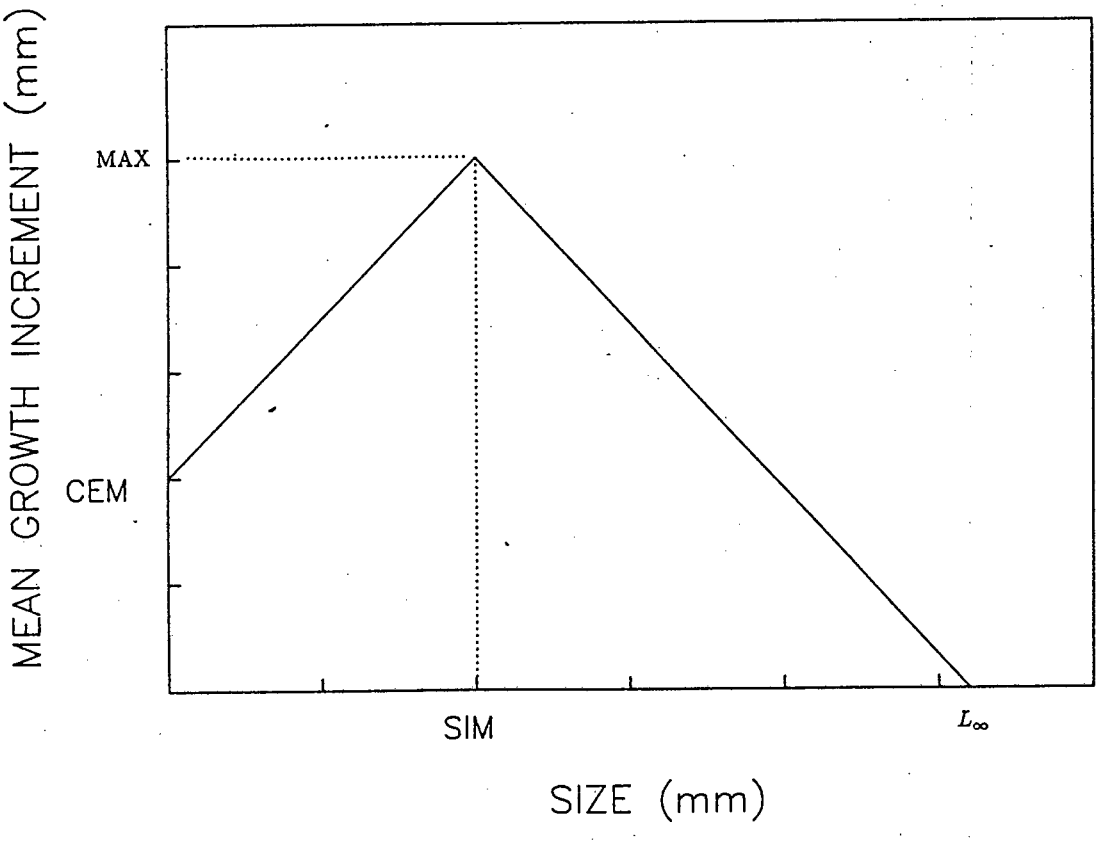

FIG.3: A model of growth rates for lobsters showing parameters used in the model

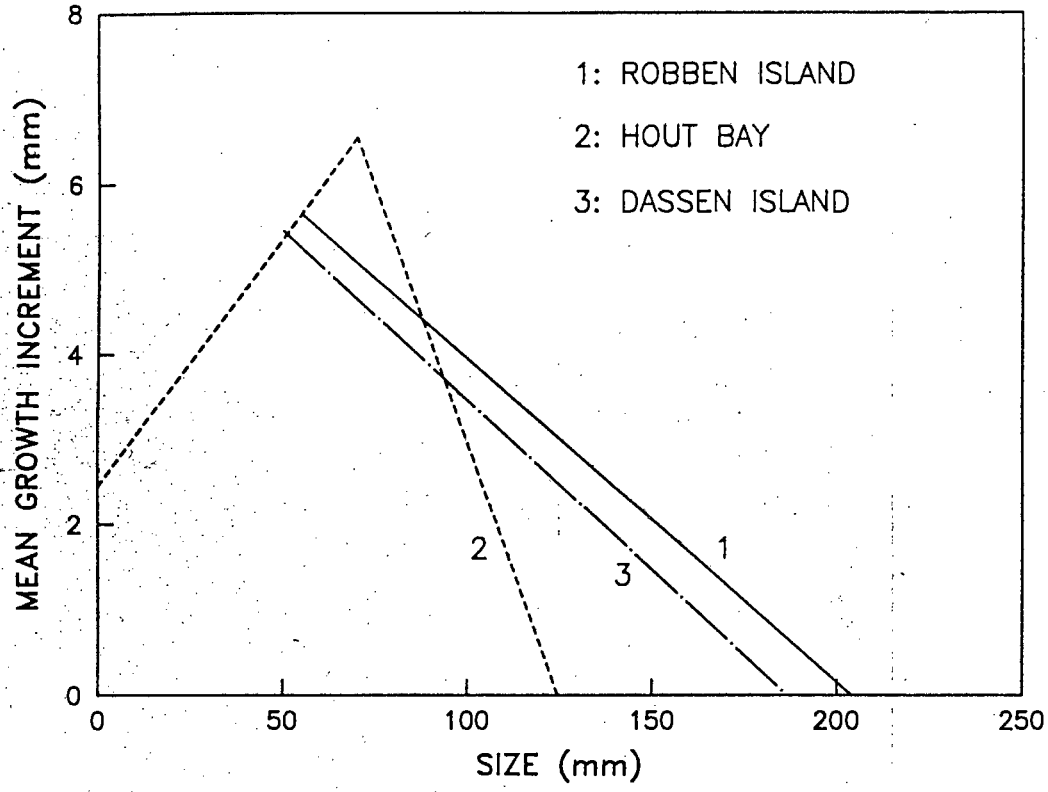

FIG.4: Growth rates for male rock lobsters

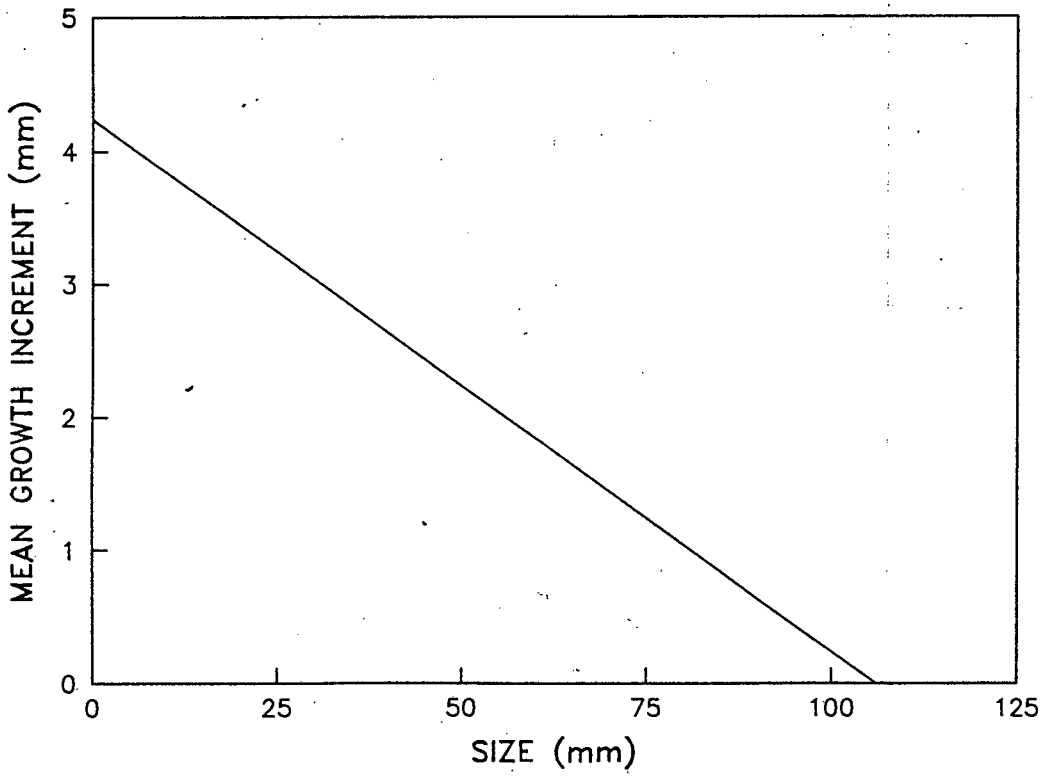

FIG.5: Growth rates for female rock lobsters

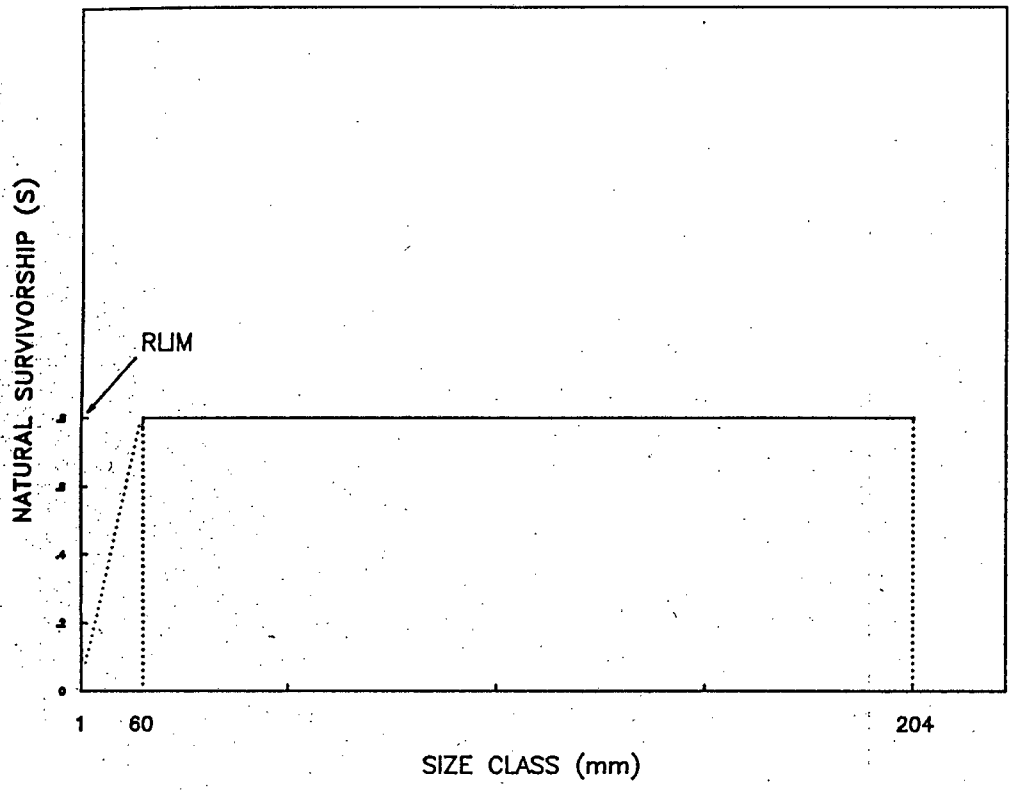

FIG.6: The dependence of natural survivorship on size.

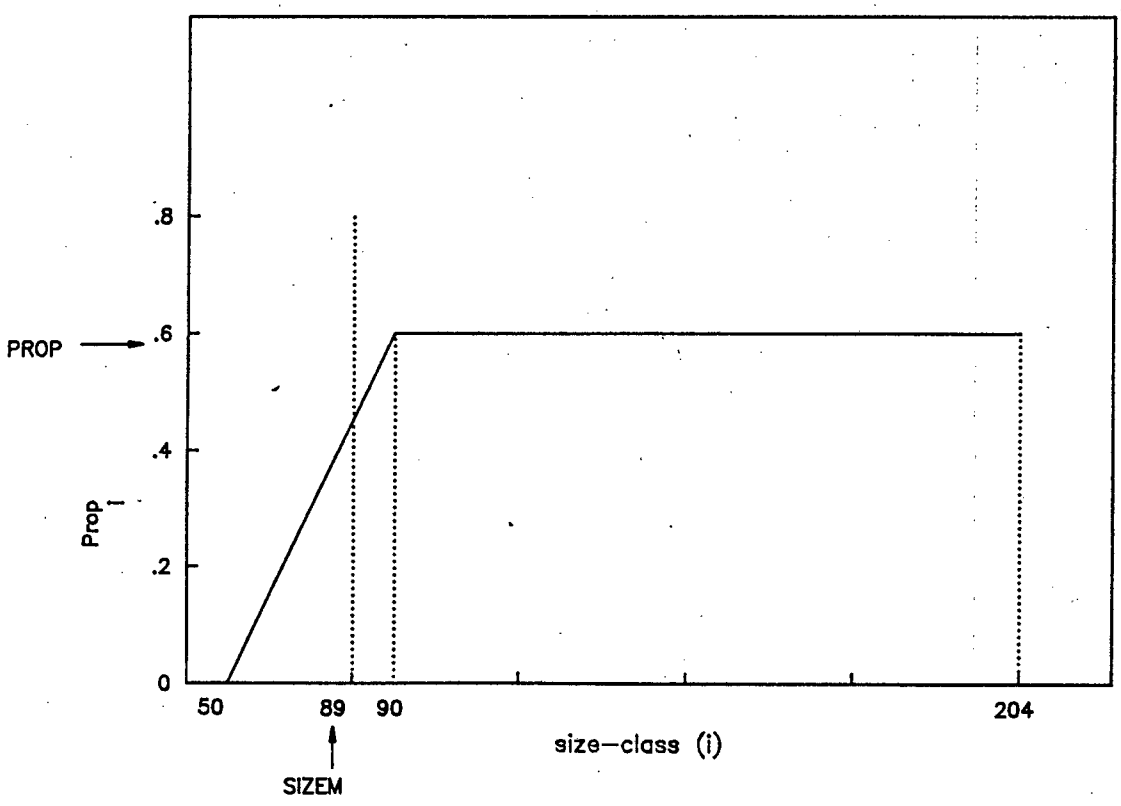

FIG.7: Fishing selectivity for rock lobsters

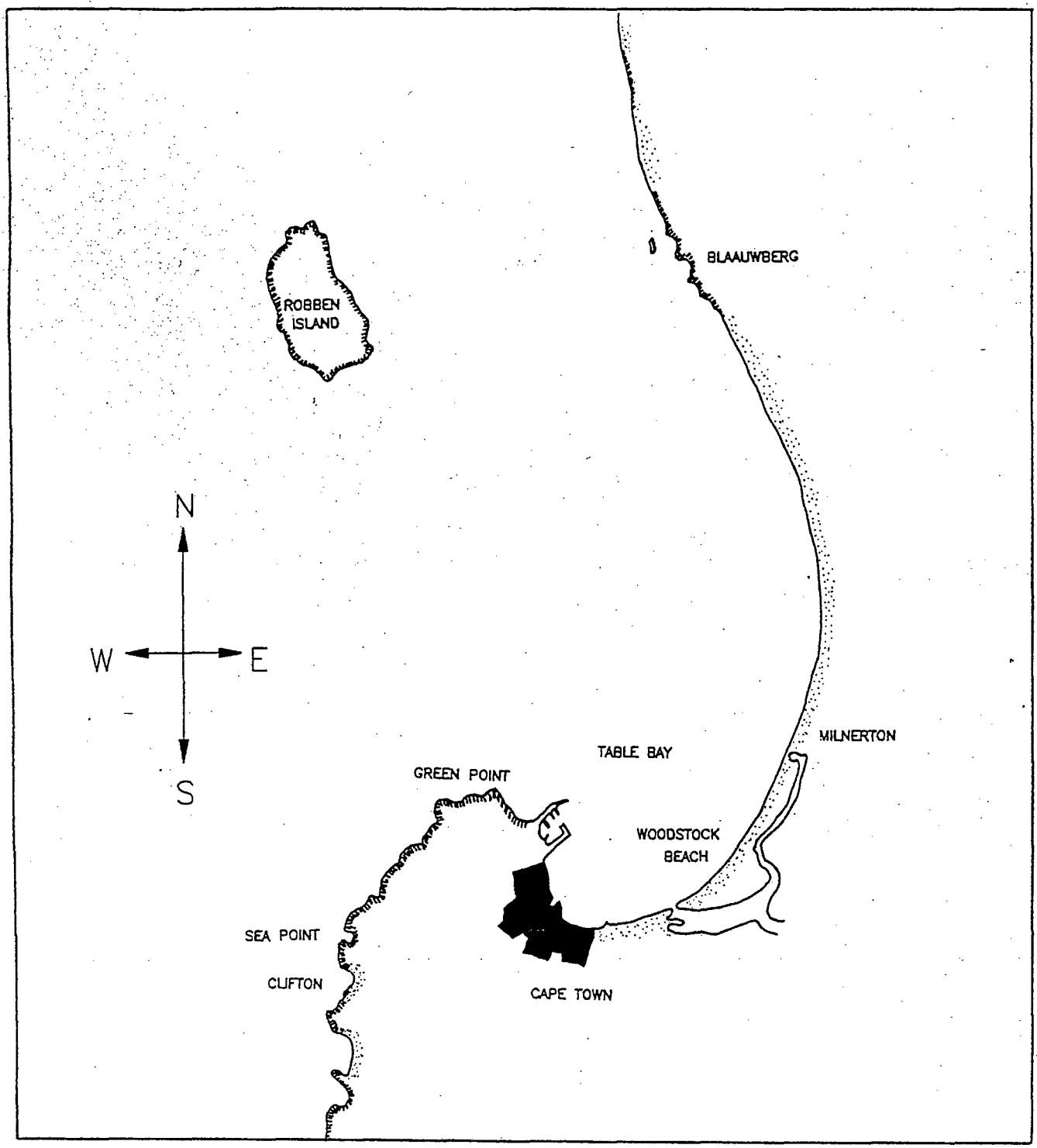

FIG.8: Areas sampled by Gilchrist between 1913–1918.

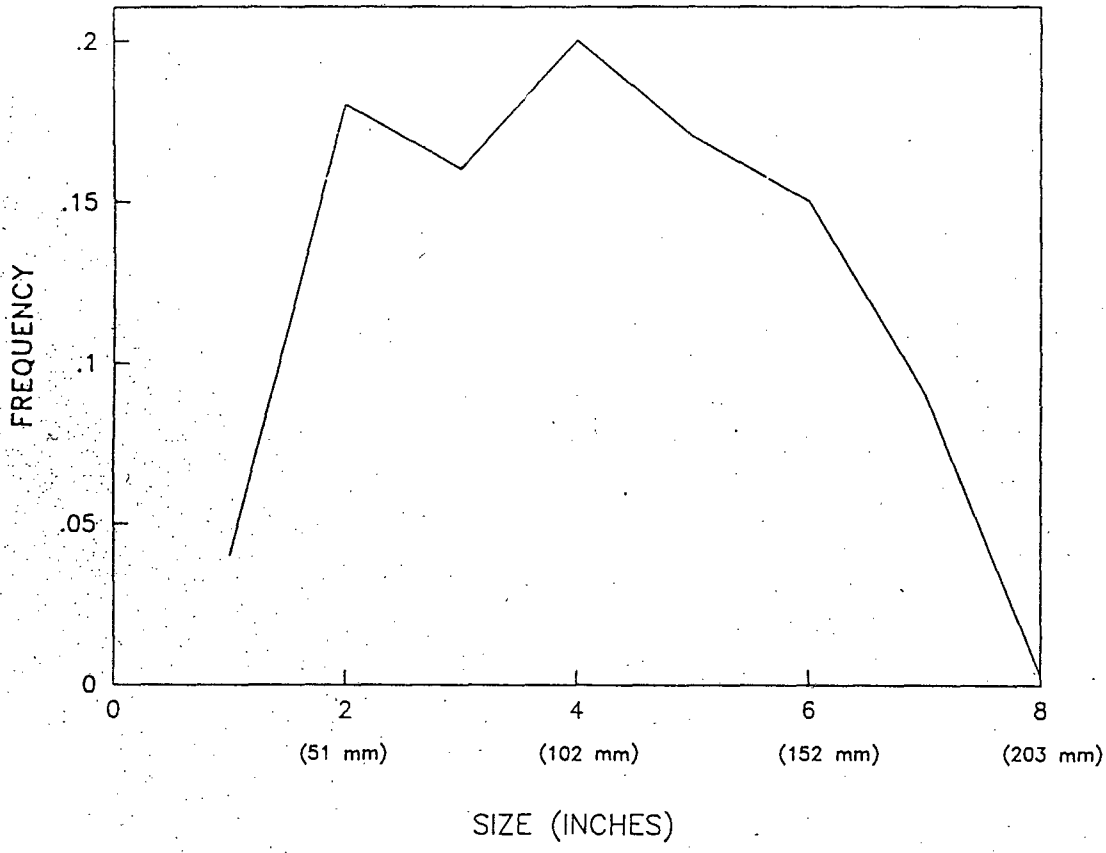

FIG.9: Pristine size frequency calculated from Gilchrists catch data (1913–1918) using hoopnets, for the Robben Island area.

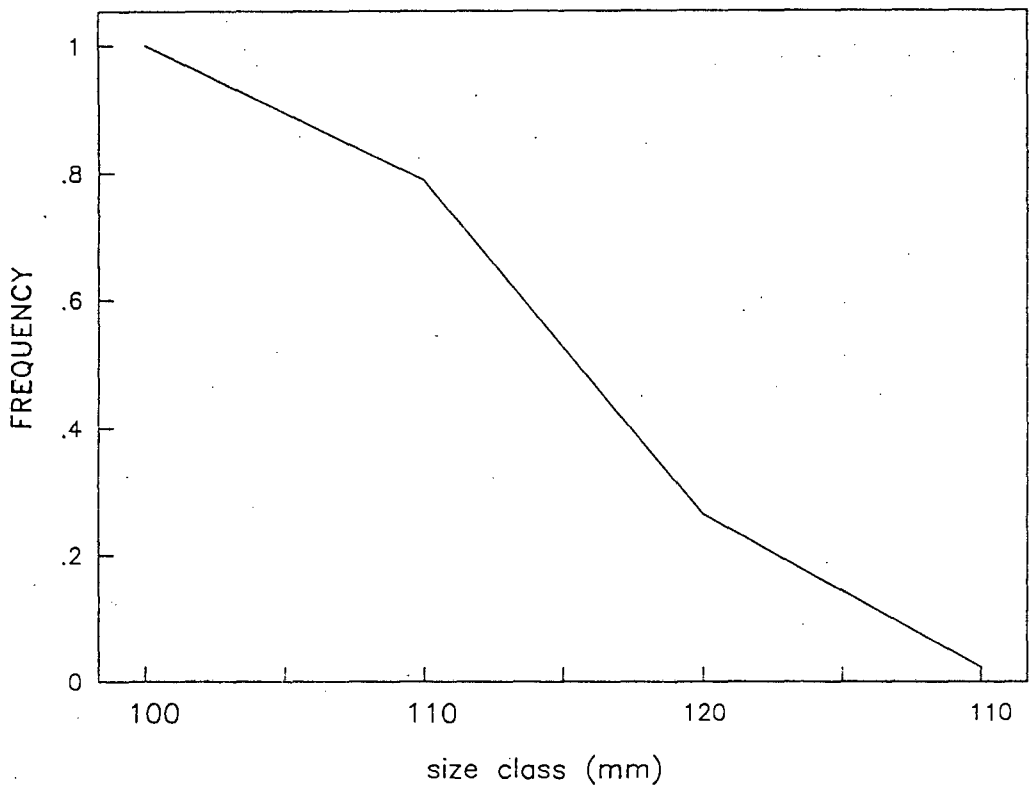

FIG.10: Observed "pristine" size frequency for Hout Bay
(data used – from SFRI catches made with traps)

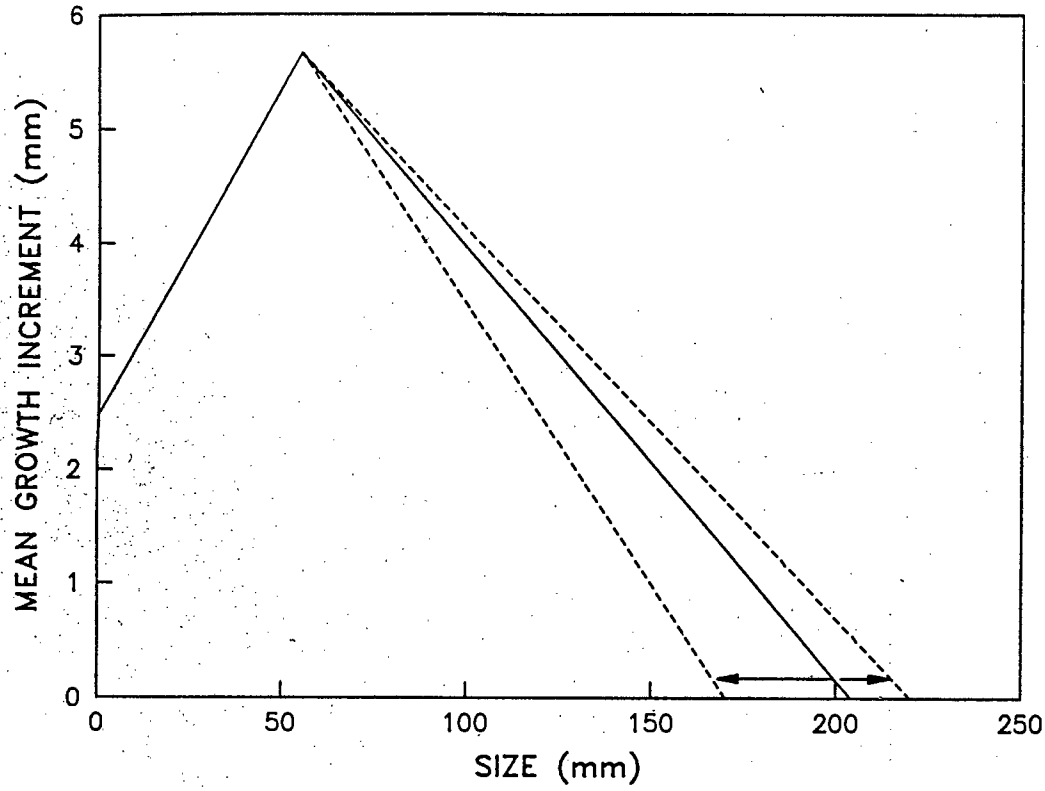

FIG.11: Sensitivity Test 1: Changing the value of L_∞

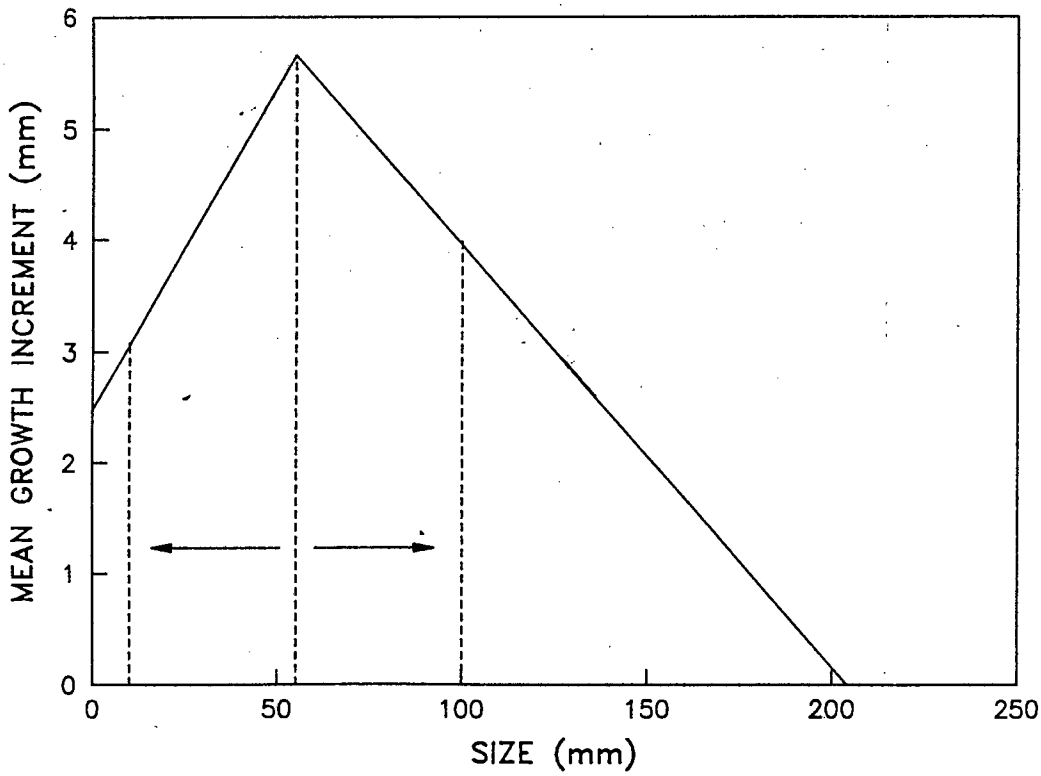

FIG.12: Sensitivity Test 2: Changing the value of SIM

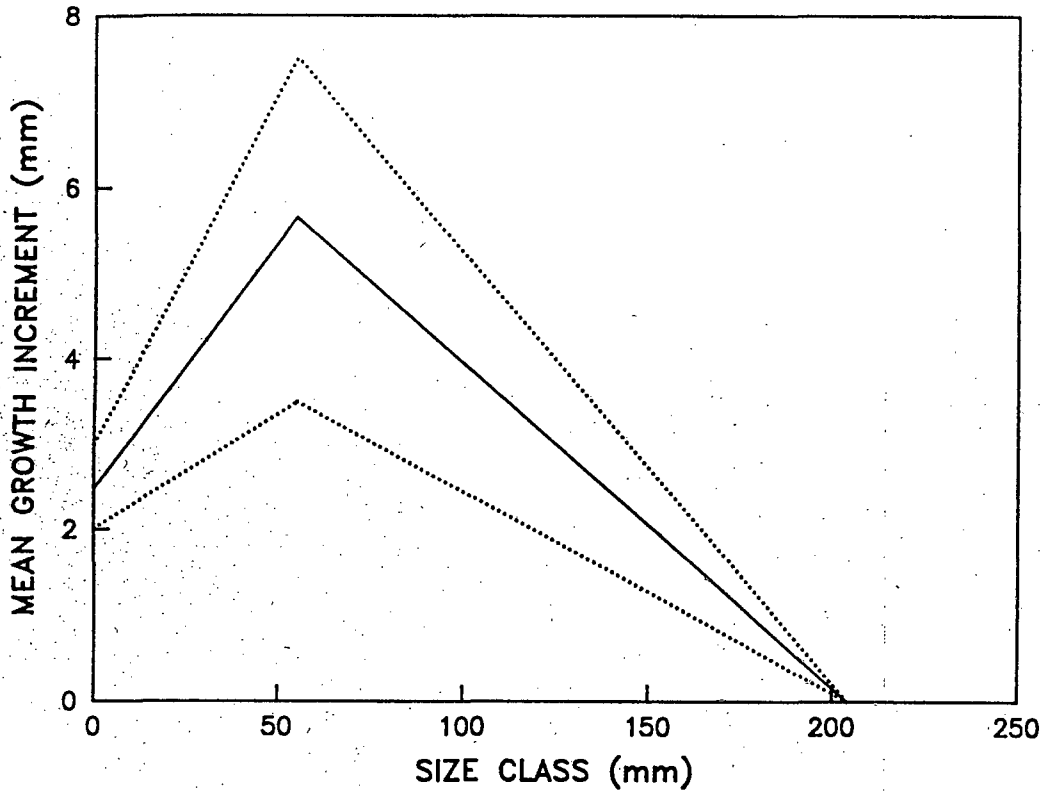

FIG.13: Sensitivity Test 3: Changing the mean growth increment values

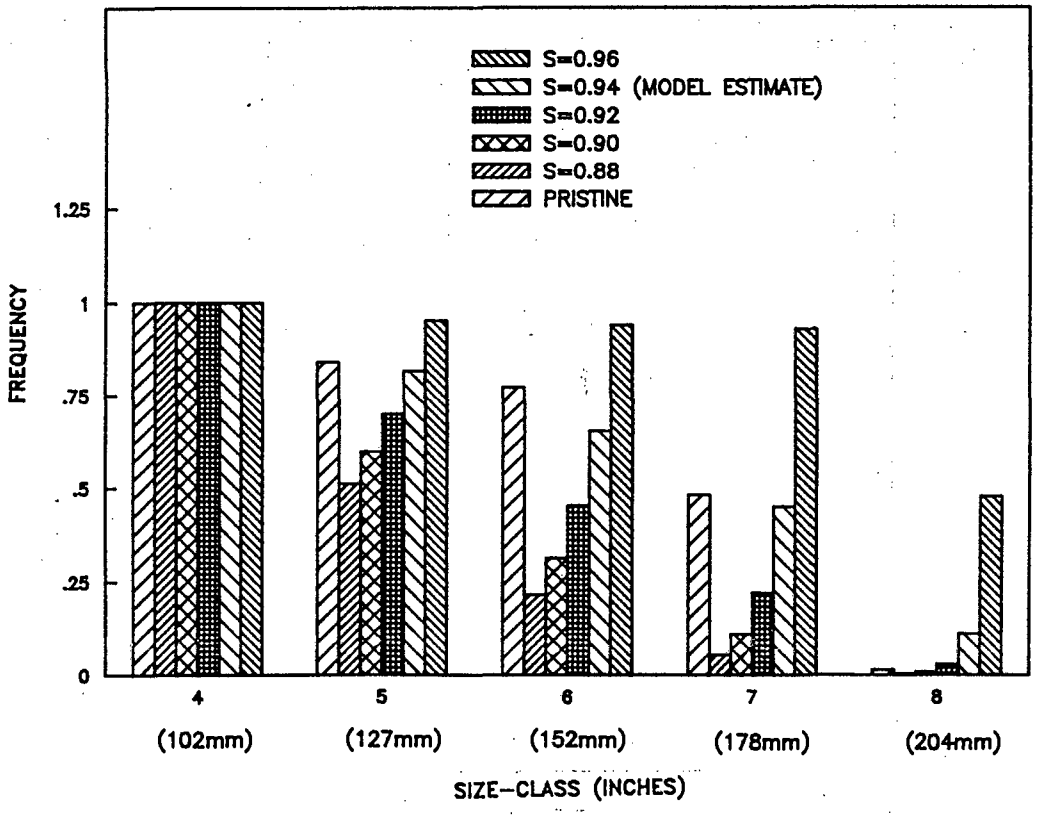

FIG.14: Observed (pristine) and fitted size frequencies for Robben Island lobsters.

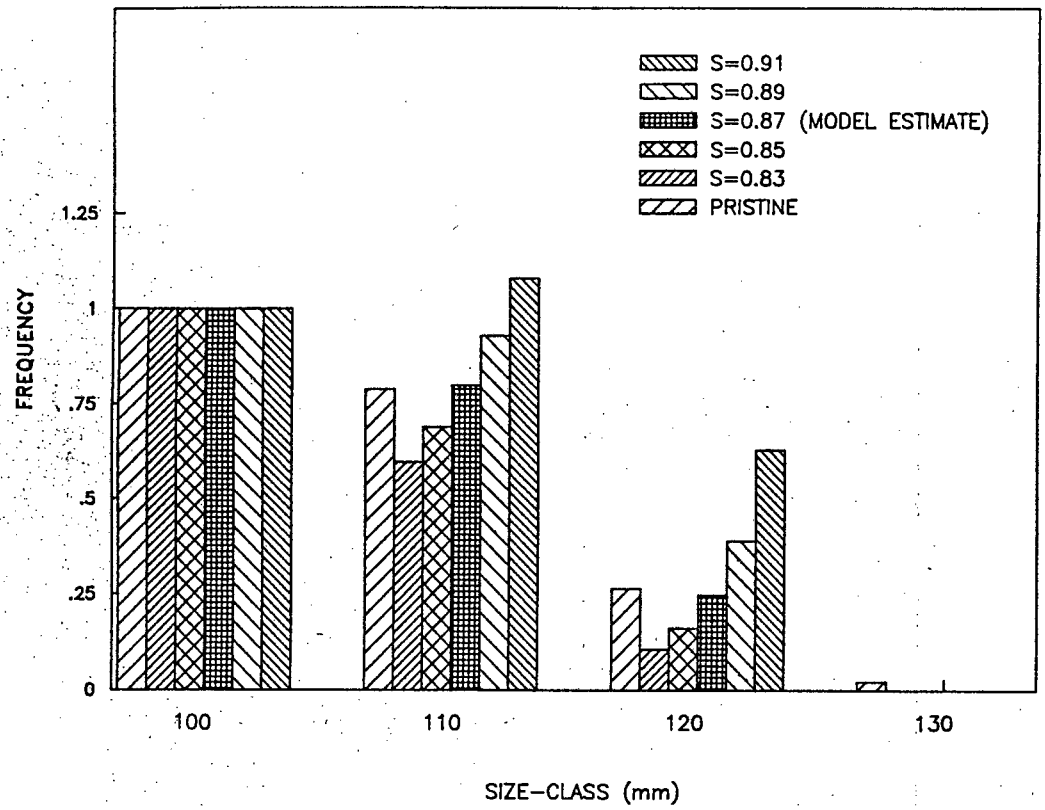

FIG.15: Observed (pristine) and fitted size frequencies for Hout Bay lobsters.

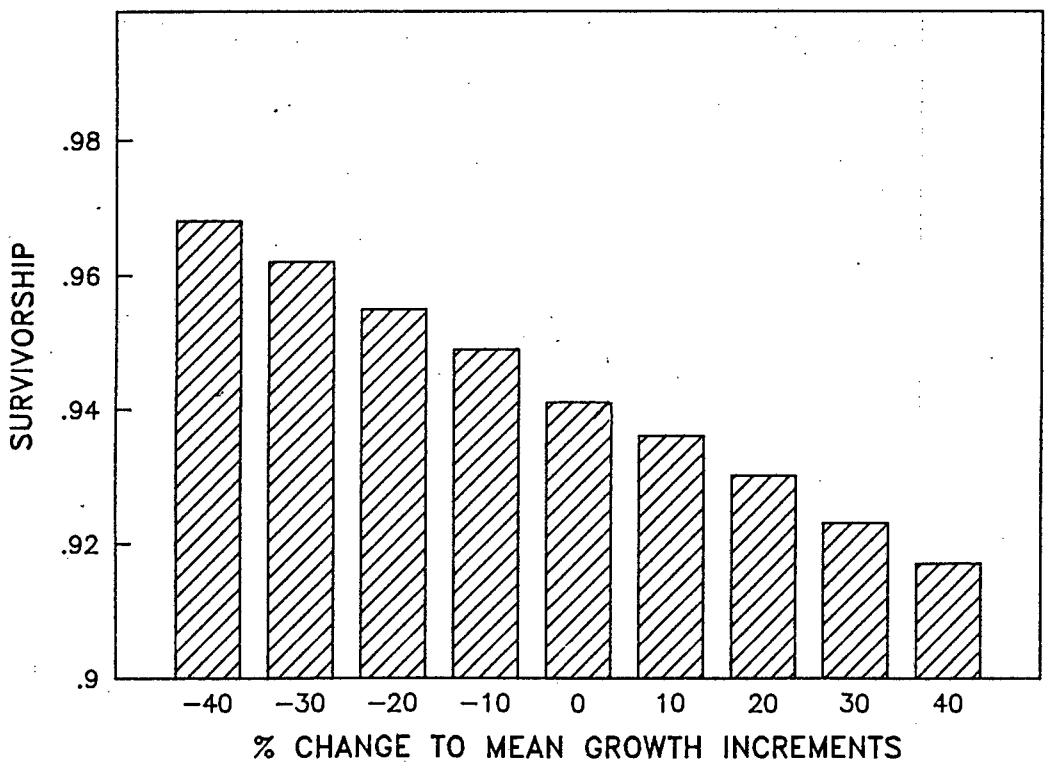

FIG.16: Natural survivorship estimates for different growth rates for Robben Island lobsters.

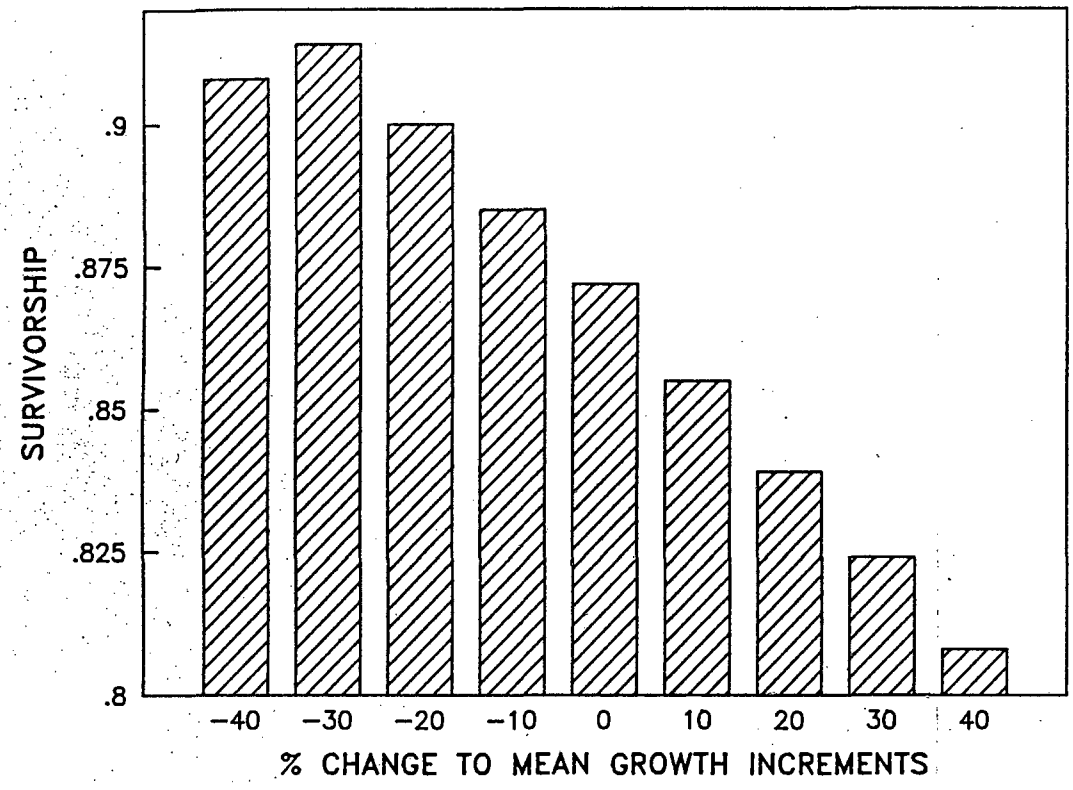

FIG.17: Natural survivorship estimates for different growth rates for Hout Bay lobsters.

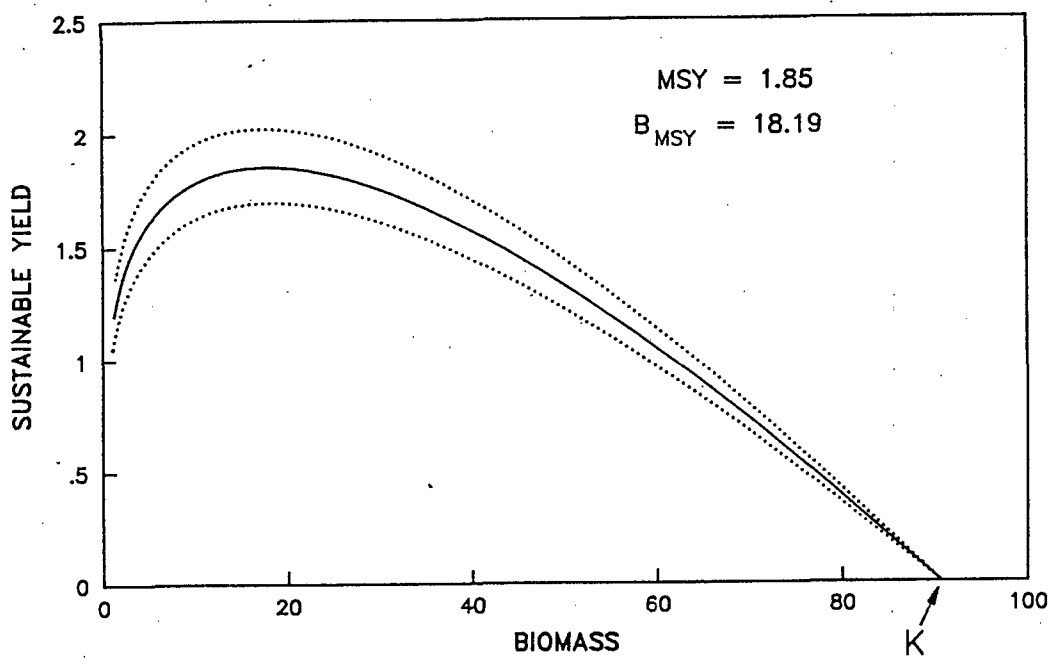

FIG.18: Sustainable yields for Robben Island lobsters (mean s estimate and 68% confidence limits)

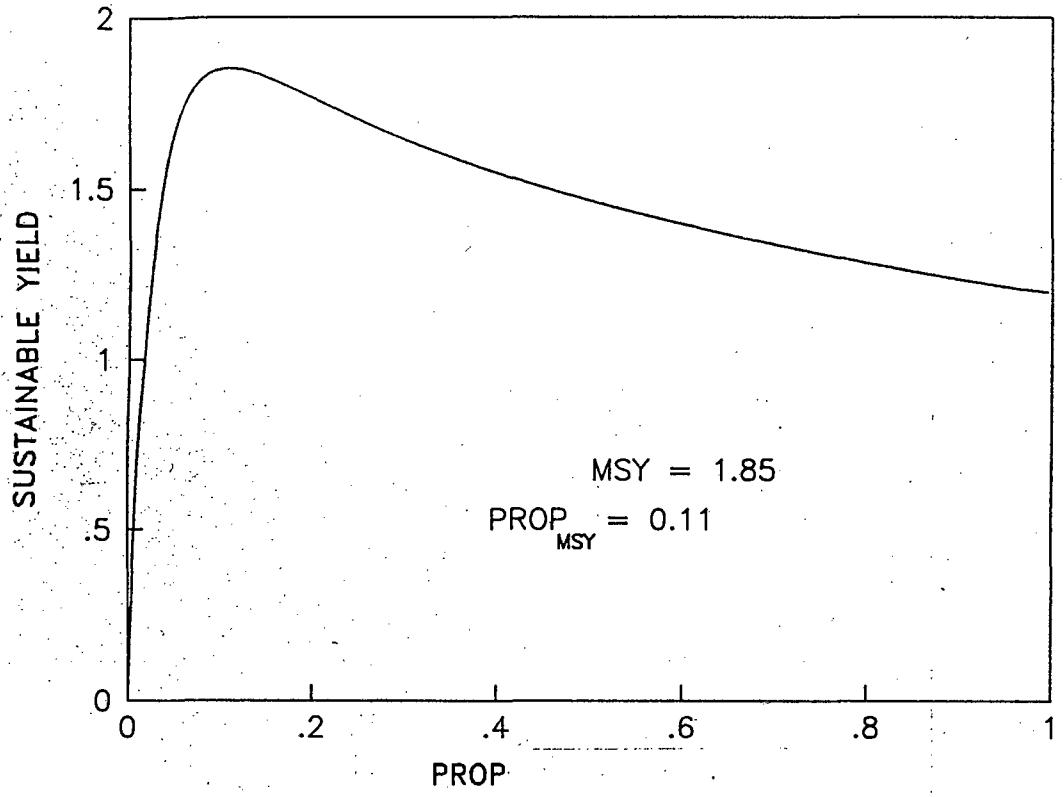

FIG.19: Sustainable yields for Robben Island lobsters under different harvest proportions, $\overline{PROP}$

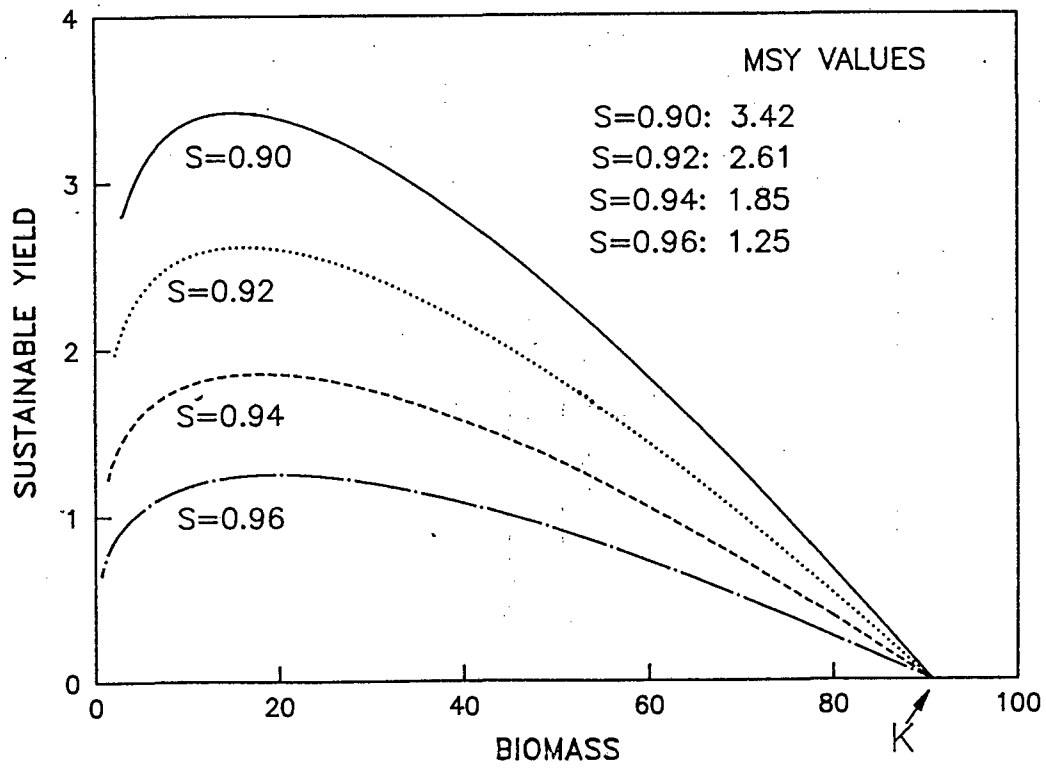

FIG.20: Sustainable yields for Robben Island lobsters under different survivorship estimates

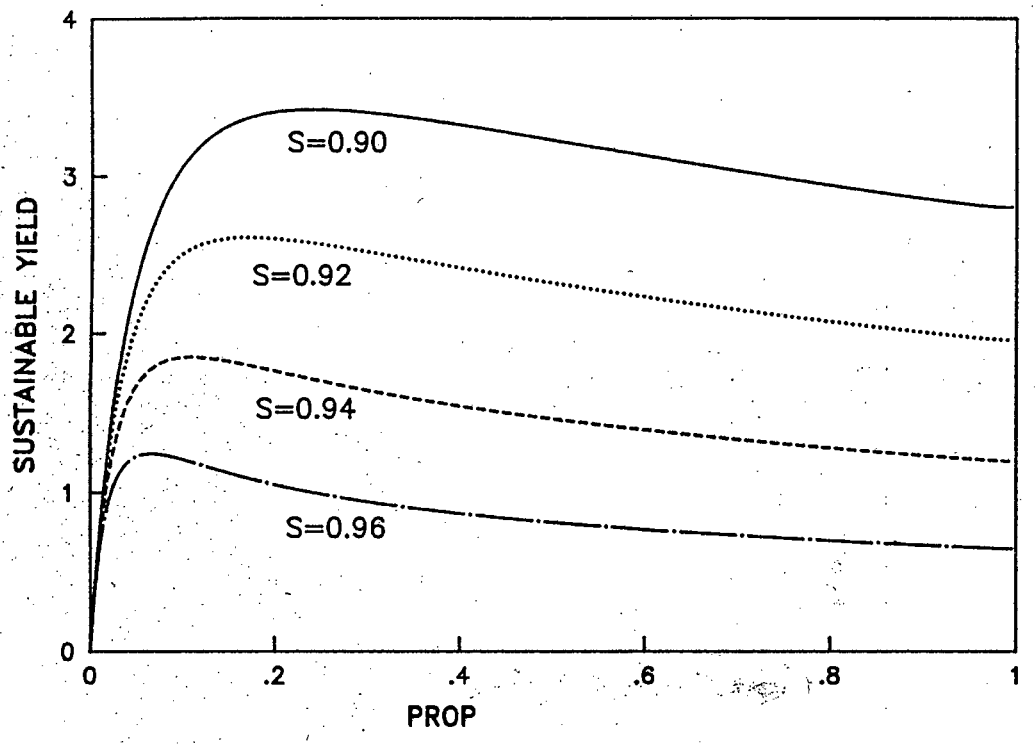

FIG.21: Sustainable yields for different harvest proportions, PROP, under different survivorship estimates for Robben Island lobsters

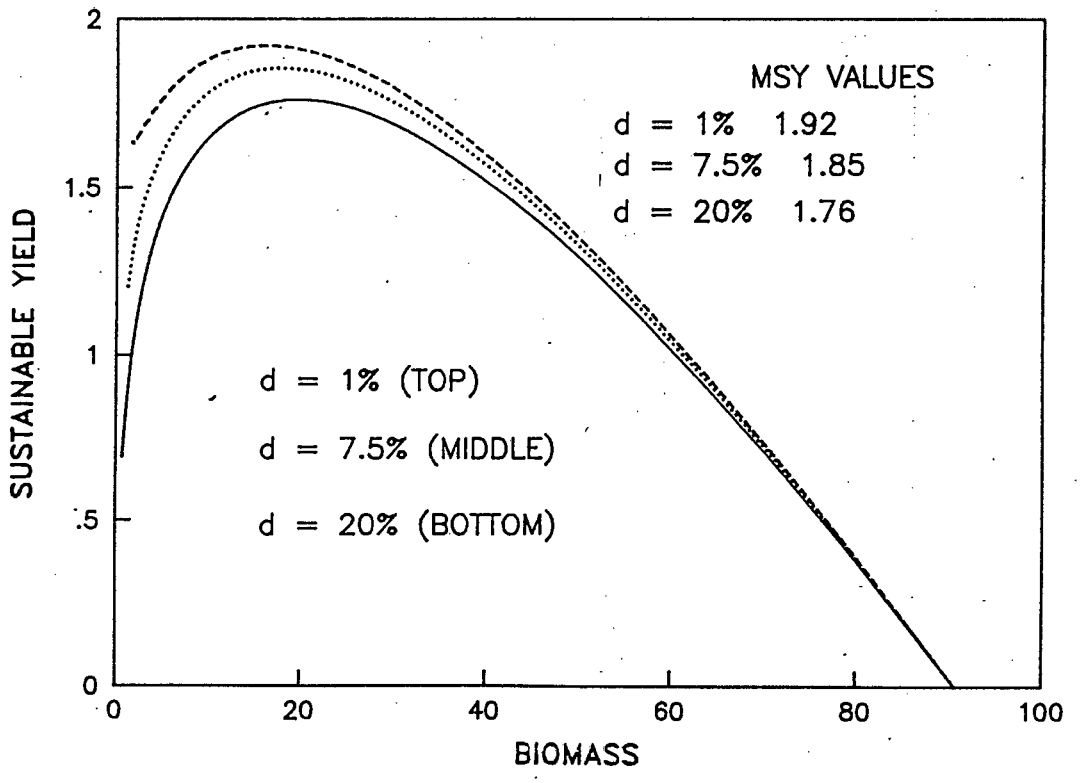

FIG.22: Sustainable yields under different discard mortalities (d) for Robben Island lobsters.

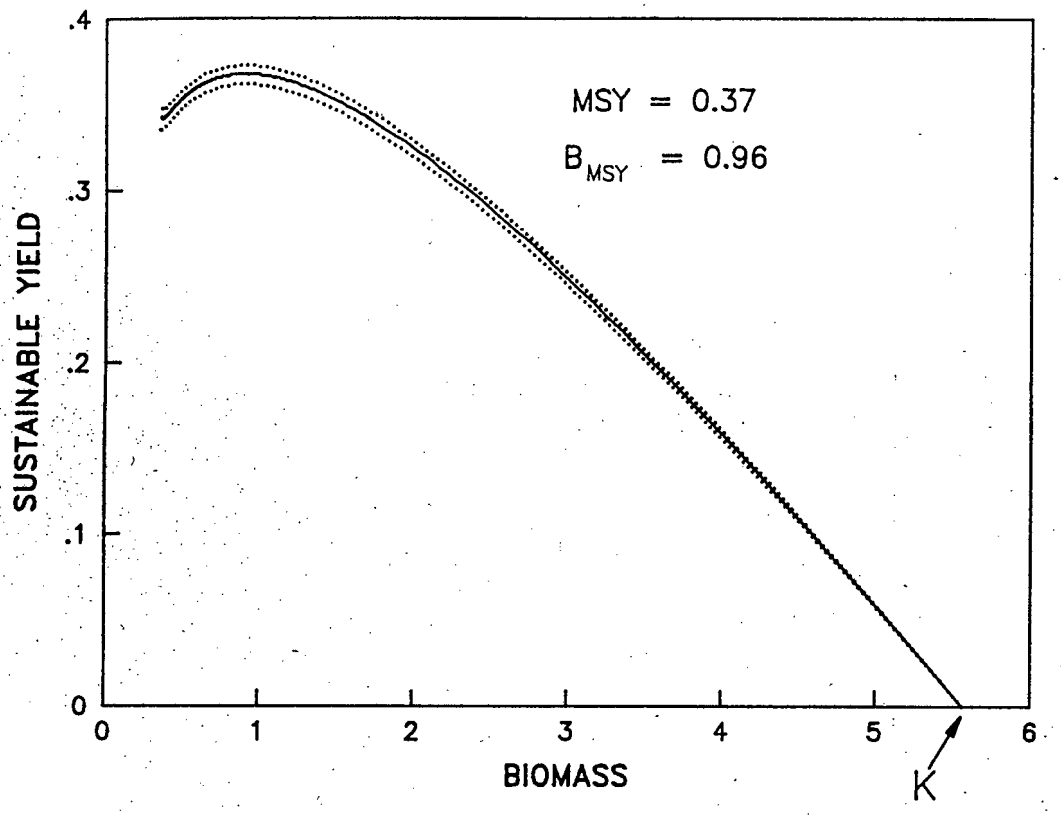

FIG.23: Sustainable yields for Hout Bay lobster
(mean natural survivorship + 68% confidence limits)

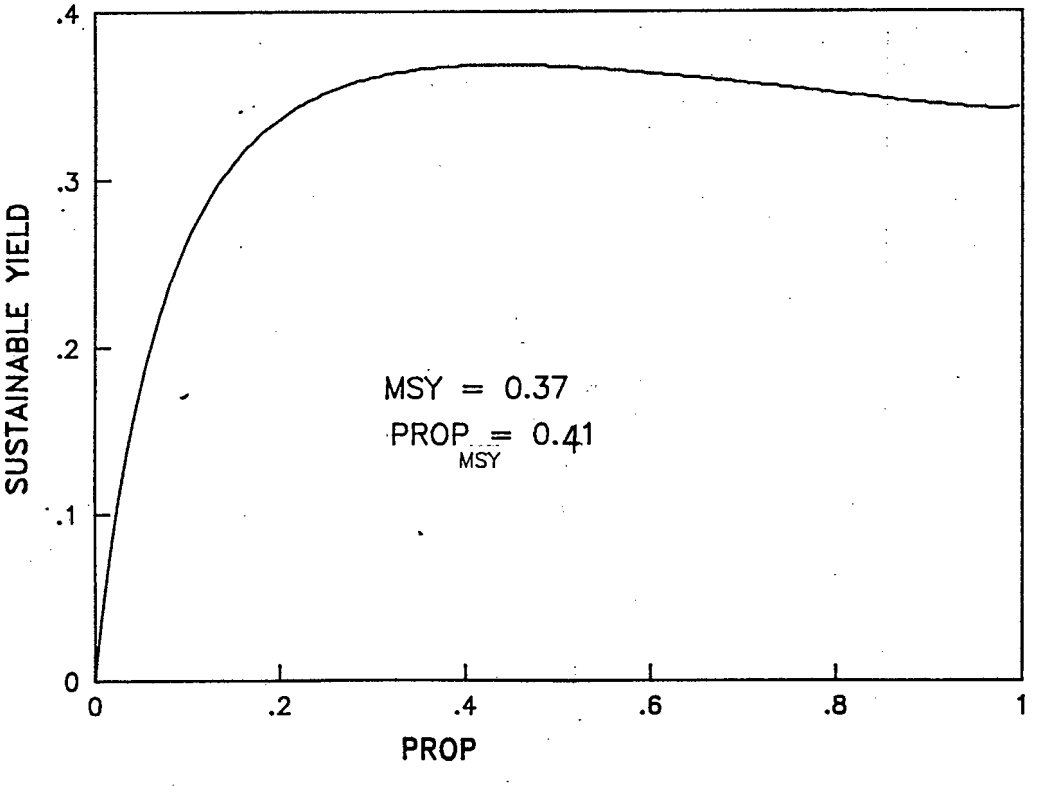

FIG.24: Sustainable yields for Hout Bay lobsters
under different PROPs

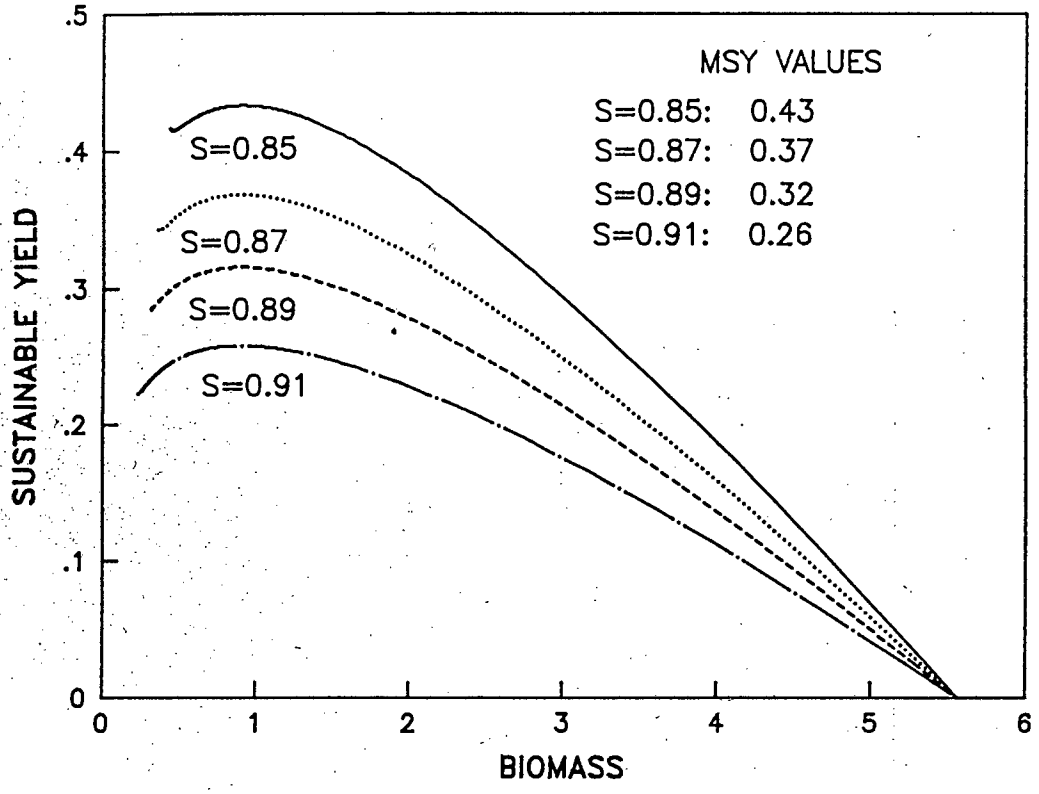

FIG.25: Sustainable yields for Hout Bay lobsters under different natural survivorship estimates

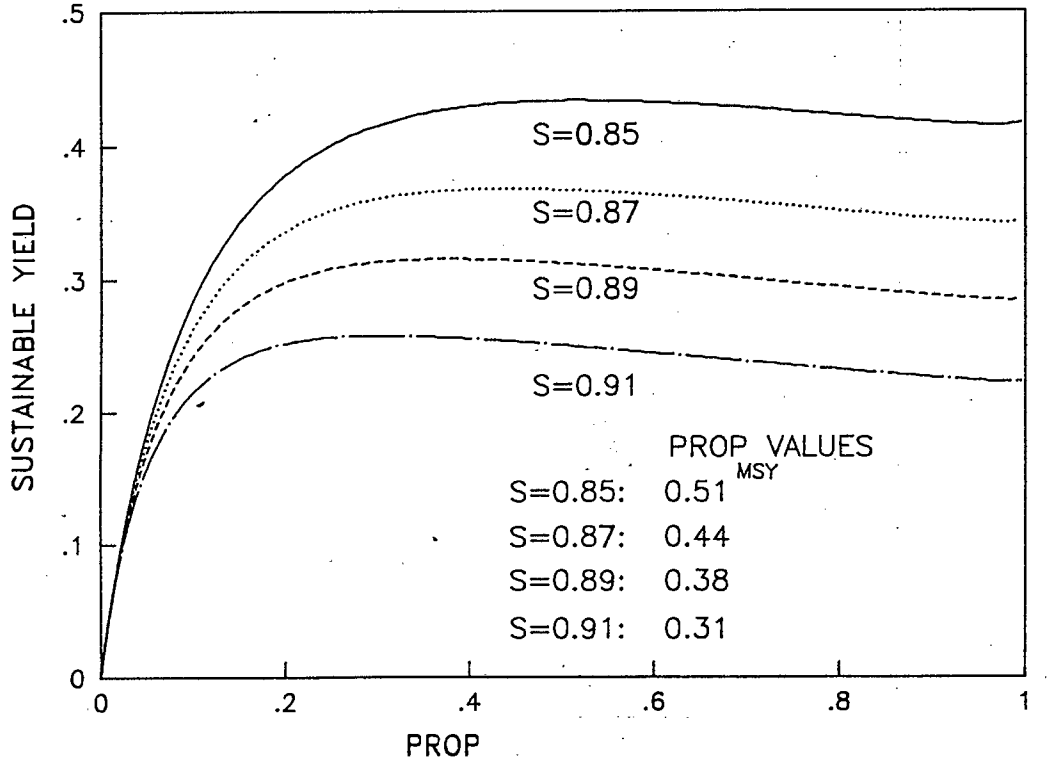

FIG.26: Sustainable yields for Hout Bay lobsters for different harvest proportions, under different natural survivorship estimates.

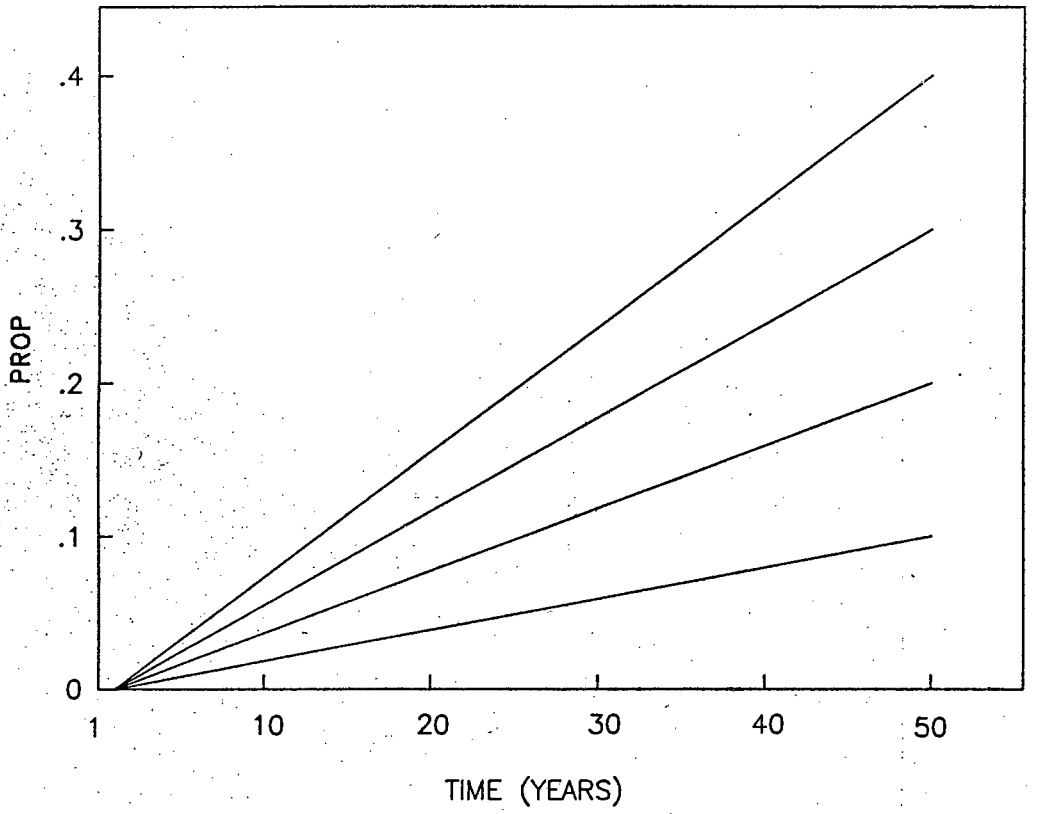

FIG.27: Scenarios of projected PROPs for 50 years (year 1 = pristine state of the population) for the Robben Island Region

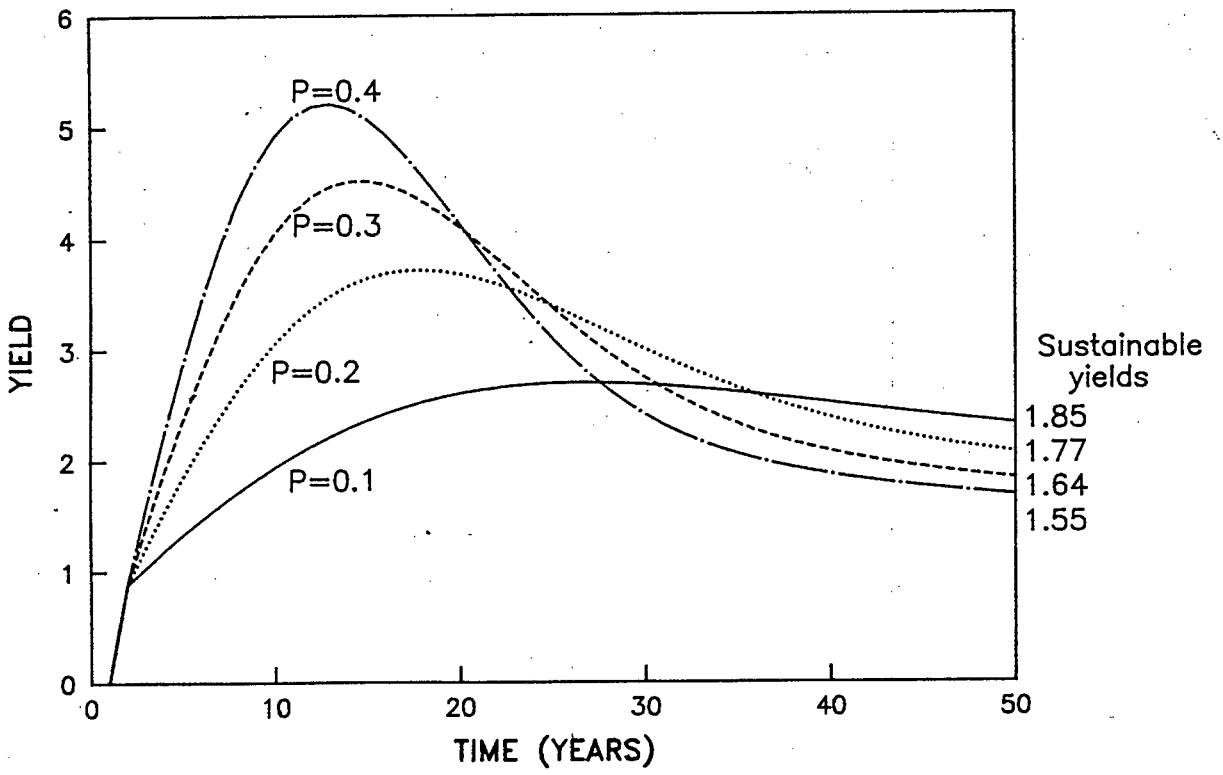

FIG.28: Projected yields for Robben Island lobsters for different prop(p) scenarios

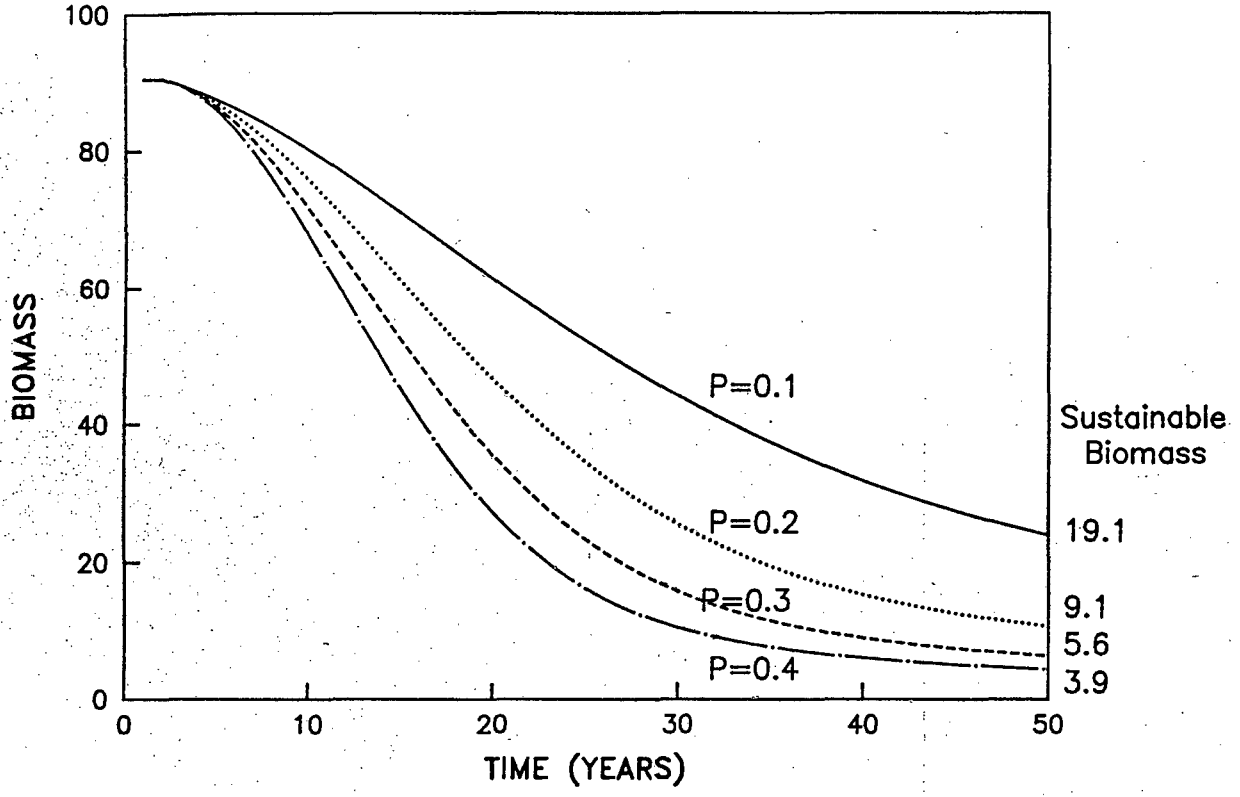

FIG.29: Projected biomass trends for Robben Island lobsters for different prop (p)

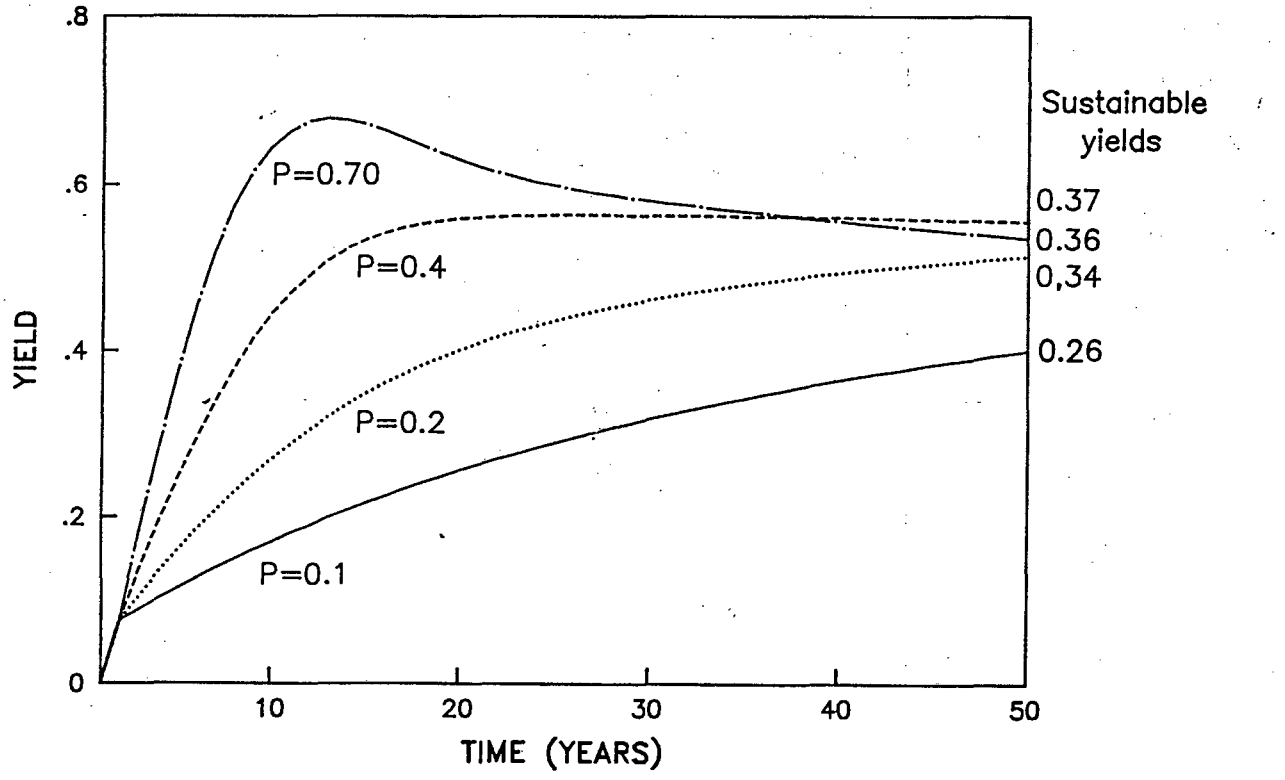

FIG.30: Projected yields for Hout Bay lobsters for different prop (p) scenarios

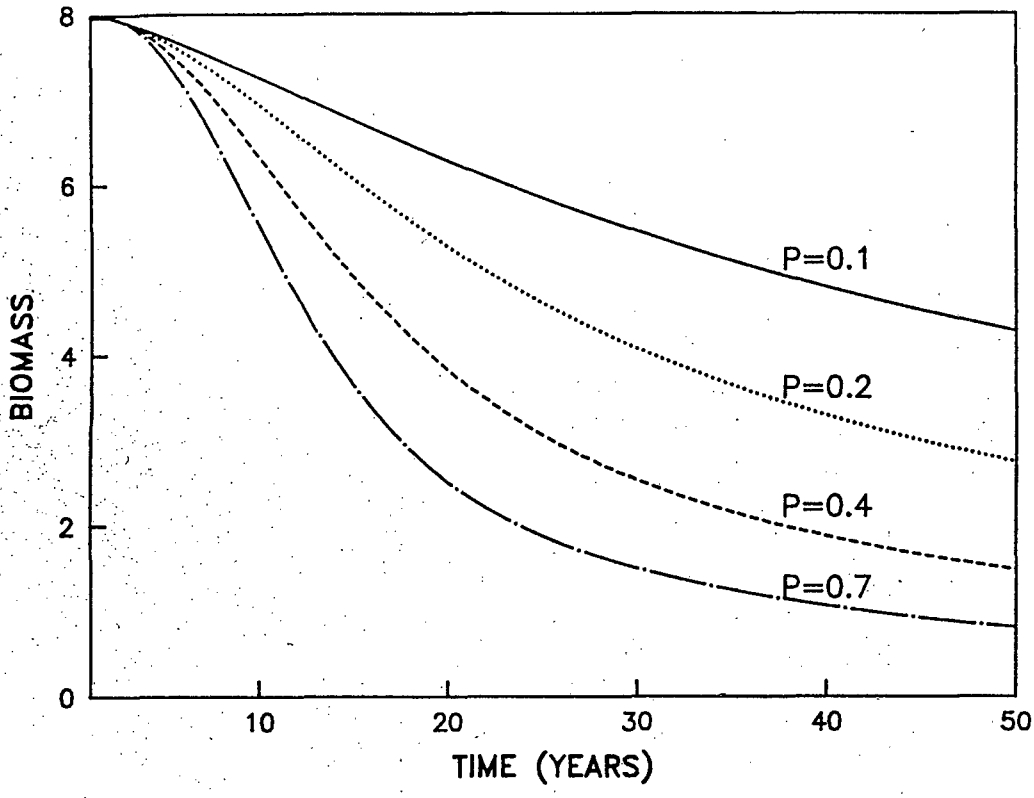

FIG.31: Projected biomass trends for Hout Bay lobsters under different prop scenarios.

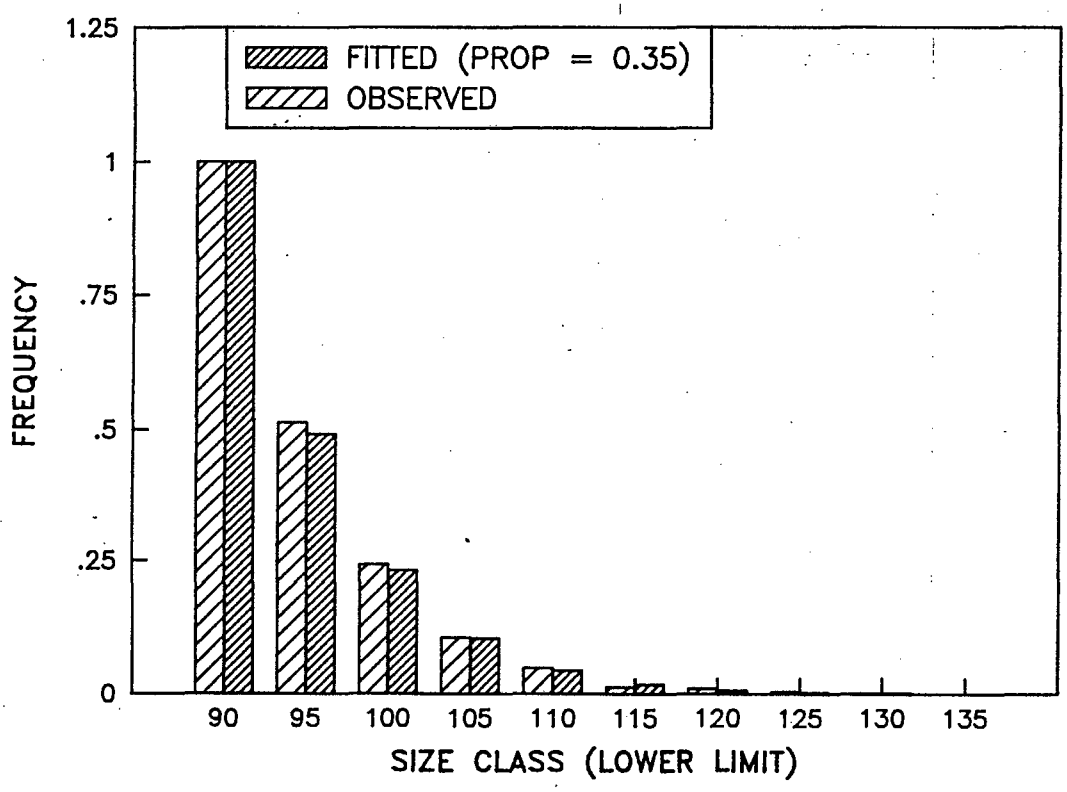

FIG.32: Observed and fitted size frequencies for Dassen Island lobsters

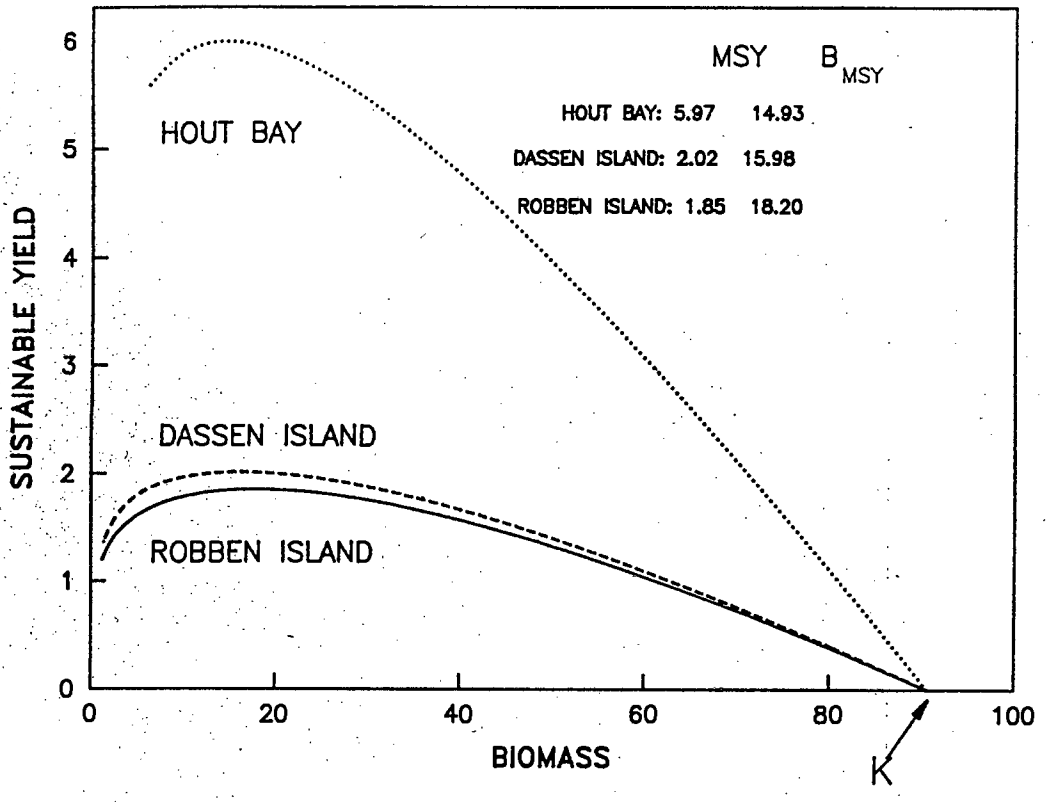

FIG.33: Relative sustainable yields for Robben Island, Hout Bay and Dassen Island

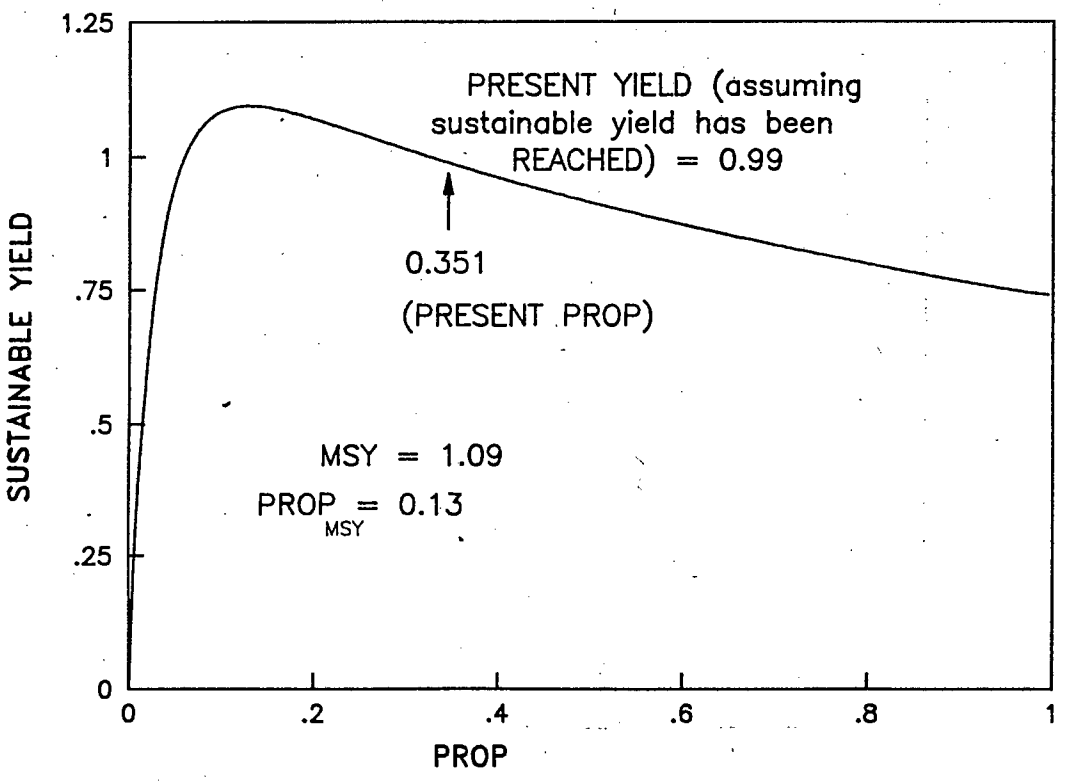

FIG.34: Sustainable yields for Dassen Island lobsters under different props.

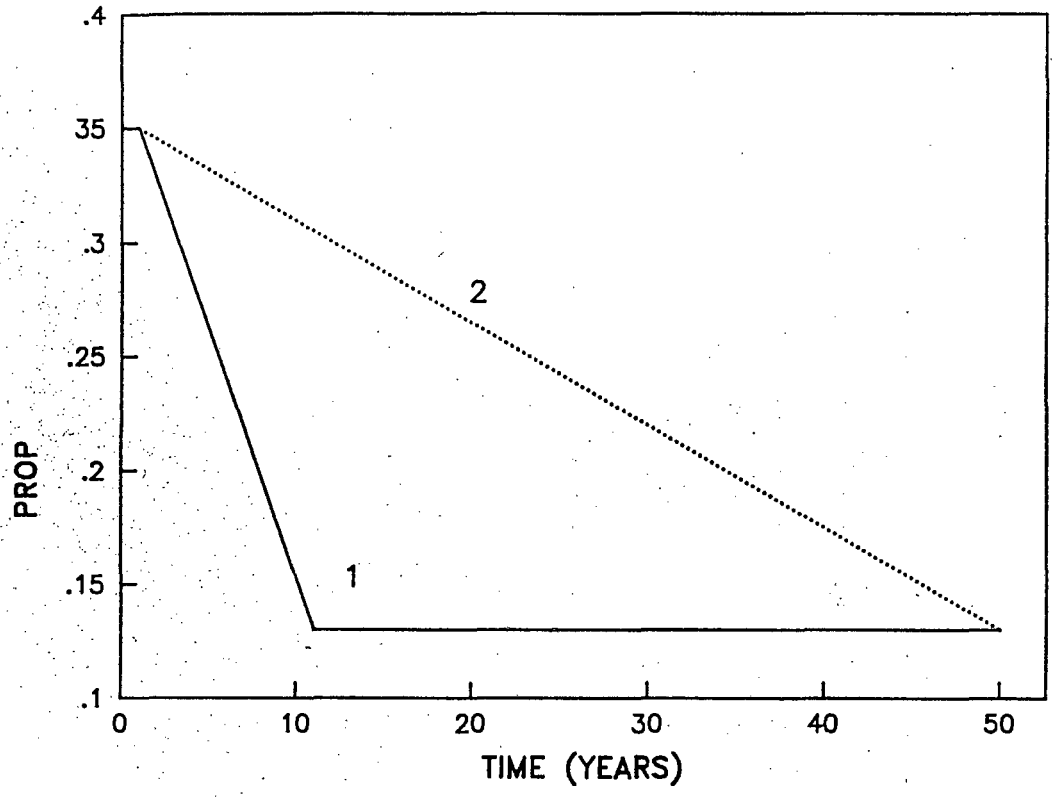

FIG.35: Projected catch scenarios for Dassen Island

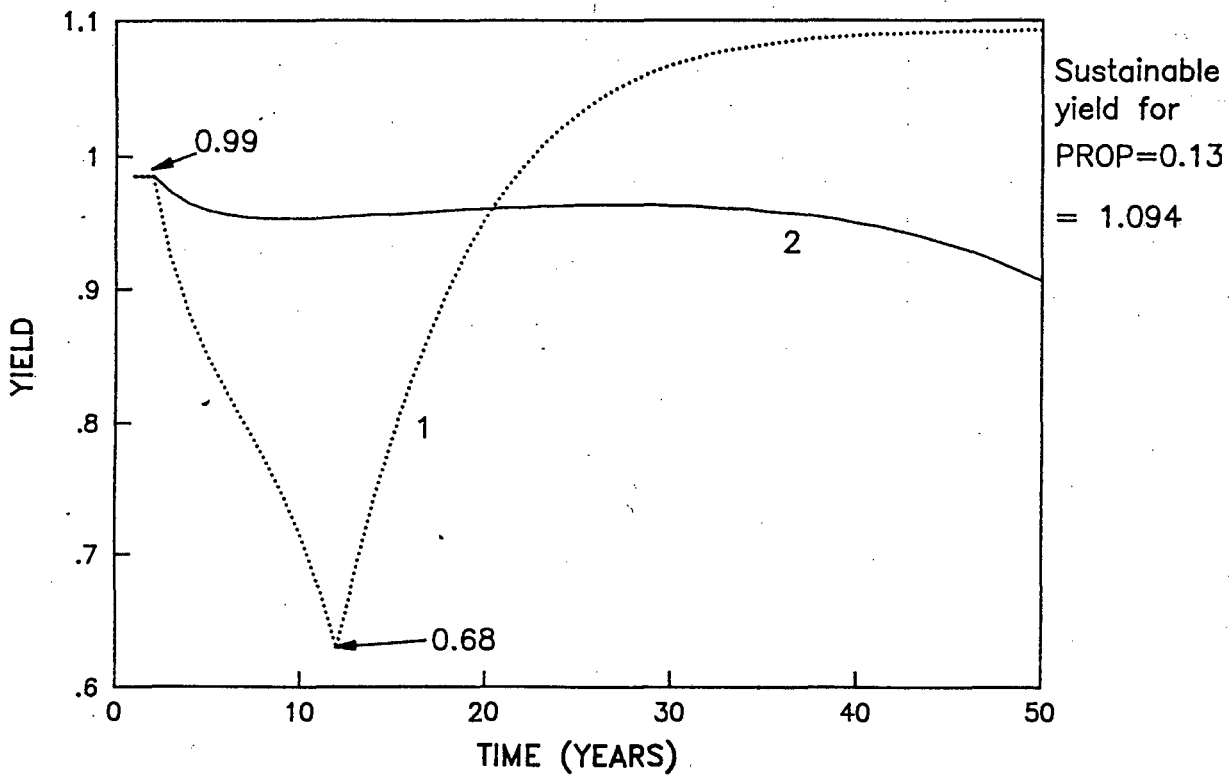

FIG.36: Projected yields for Dassen Island lobsters under two catch proportion scenarios
(scenarios correspond to those in Figure 35)

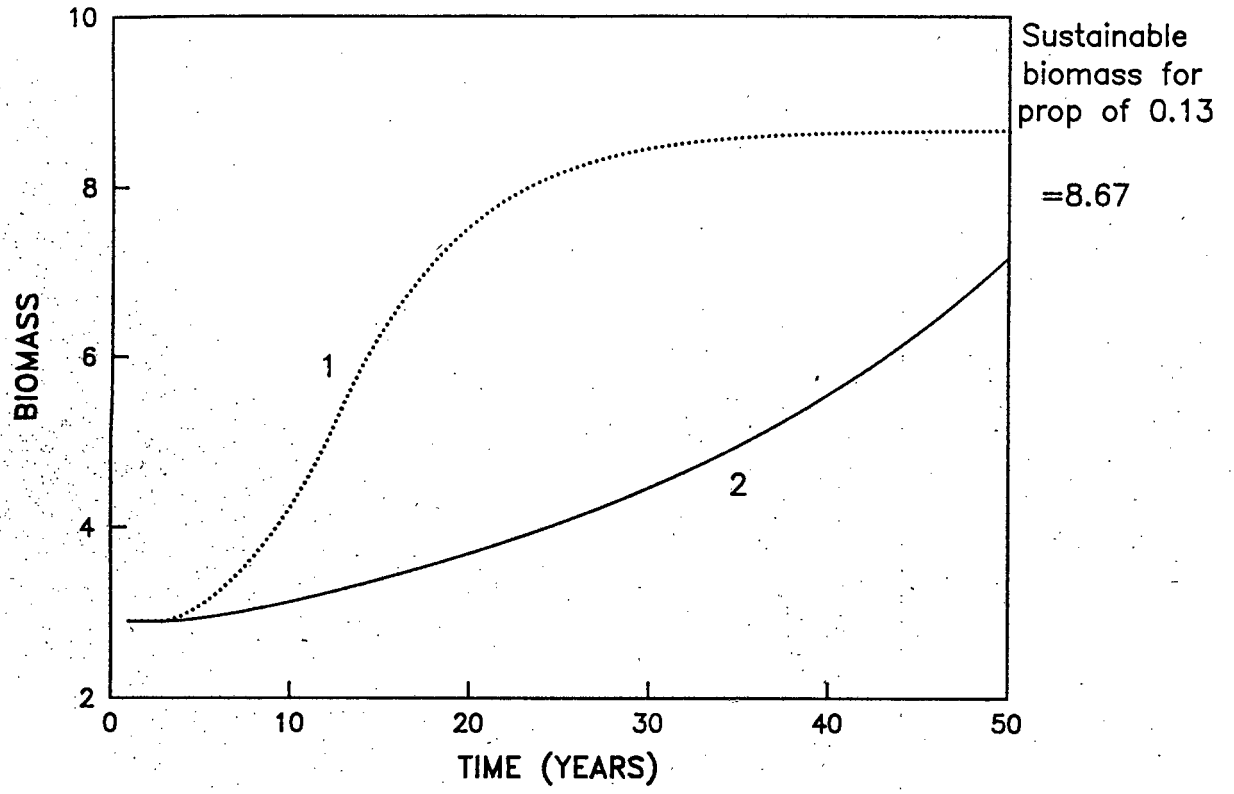

FIG.37: Projected biomass trends for Dassen Island lobsters under two catch proportions
(scenarios correspond to those in Figure 35)

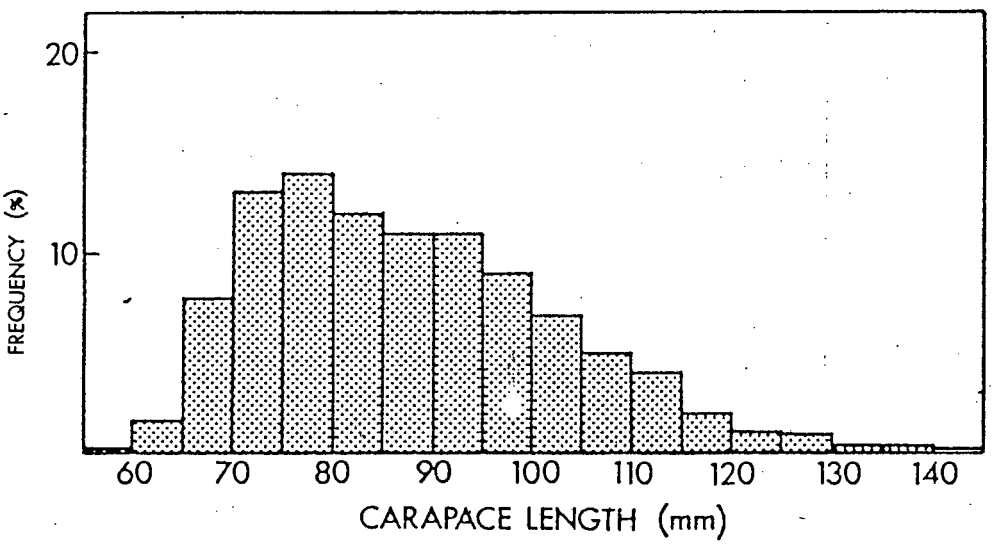

FIG.38: Length frequency distribution of male rock lobsters at Robben Island. (Pollock 1987).

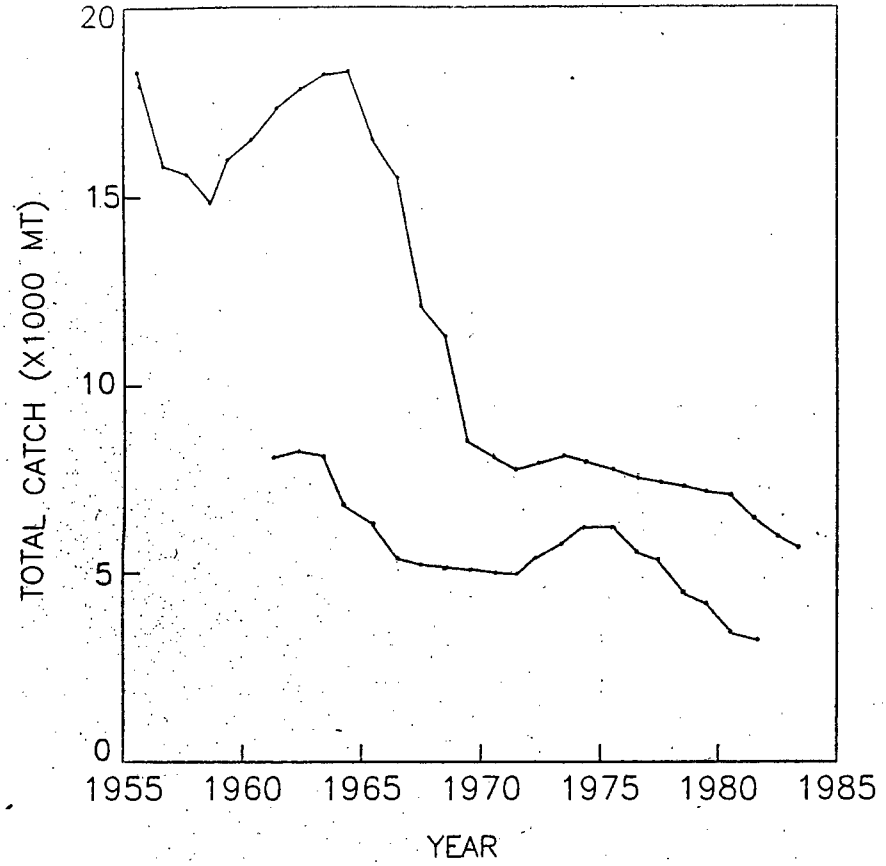

FIG.39: Historic rock lobster catches in :
1) Western Cape
2) All Areas
(Pollock & Shannon 1987)

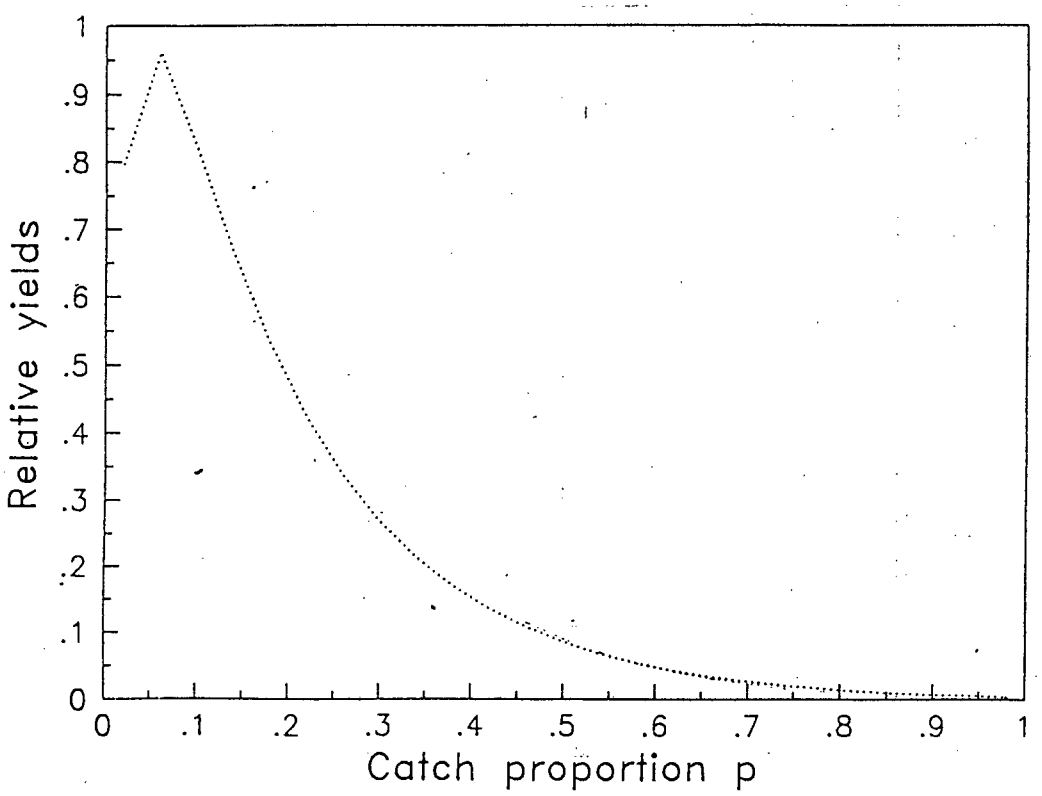

FIG.40: Sustainable yields in Zone A at different catch proportions (p) for adult survivorships of s=0.96 and discard mortality of 15% (Barkai and Bergh 1990)

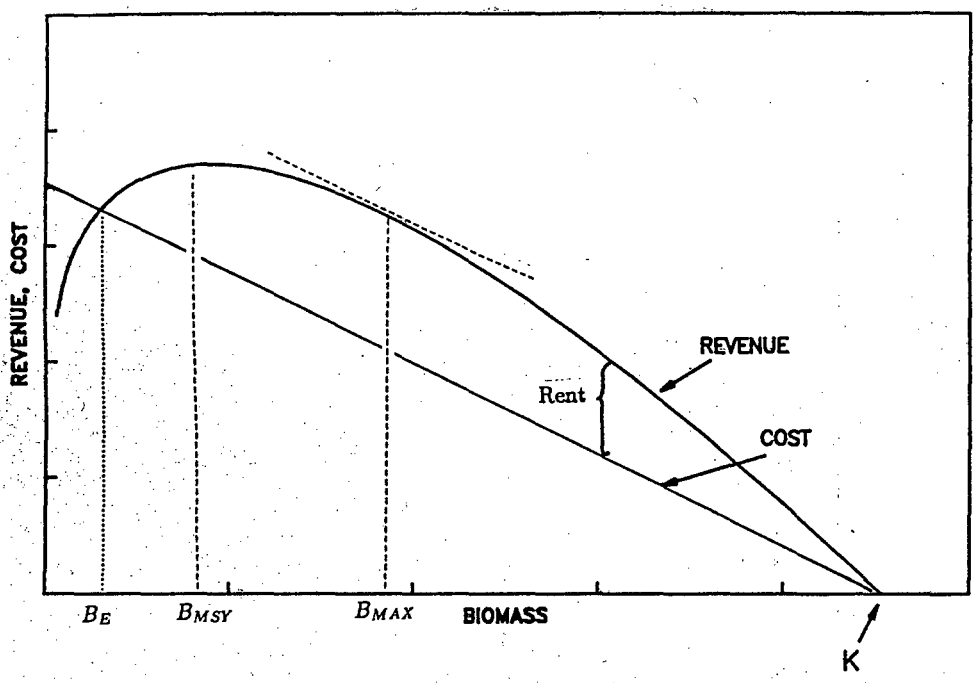

FIG. 41: Cost and Revenue associated with fishing, in terms of the biomass level